

GEORGIA INSTITUTE OF TECHNOLOGY
School of Aerospace Engineering

**NEW APPROACHES TO HSCT MULTIDISCIPLINARY
DESIGN AND OPTIMIZATION**

NASA Grant NGT 51102L

FINAL REPORT

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PREFACE

This report summarizes research carried out under Grant NGT 51102L, "New Approaches to HSCT Multidisciplinary Design and Optimization," from 1994 to 1998 at the Georgia Institute of Technology. The research was carried out by a multidisciplinary team of students, post doctoral fellows and faculty members in the School of Aerospace Engineering and the School of Mechanical Engineering with the support of industrial partners, Rockwell International – North American Aircraft (now Boeing Seal Beach) and Lockheed Martin (Marietta). The team leadership was as follows:

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SUMMARY

This project combined the innovations and resources of three laboratories in the Georgia Institute of Technology along with consultation, guidance, and tool-sharing from two large aerospace engineering companies. The Georgia Tech laboratories were the Aerospace Systems Design Laboratory (ASDL) in the School of Aerospace Engineering, the Systems Realization Laboratory (SRL) in the School of Mechanical Engineering, and the Parallel Processing Research Laboratory (PPRL) jointly in the School of Mechanical Engineering and the College of Computing. The synergism they provide in new approaches to multidisciplinary design and optimization (MDO) is illustrated by the Venn diagram in Figure 1.

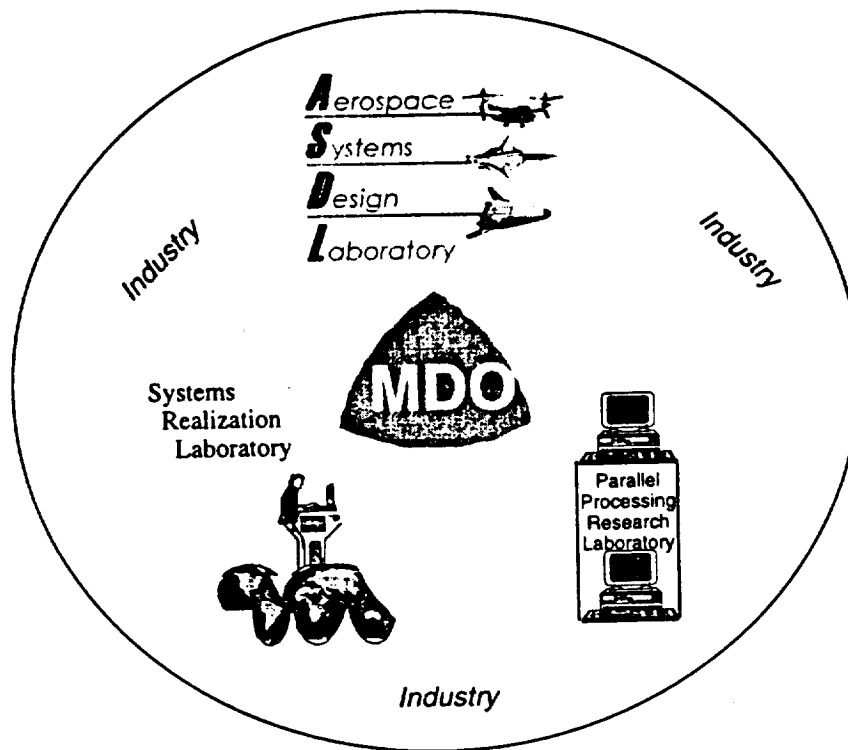


Figure 1. Coordinated University/Government/Industry Team

The two large aerospace companies were Rockwell International – North American Aircraft (now Boeing), Seal Beach, CA and Lockheed Aeronautical Systems Company (now Lockheed Martin), Marietta, GA. The ASDL brought a generic Integrated Product/Process Development (IPPD) methodology that combined systems engineering and quality engineering methods and tools into a top down design decision support process framed in a computer integrated environment. In addition, ASDL brought the computing architecture for the project research. The SRL brought the Decision Support Problem Technique (DSPT) and its implementation in DSIDES. The PPRL brought advances in parallel processing methods to help in the development and execution computing time for the multidisciplinary, high fidelity research codes being utilized in the research. The grand challenge selected as the focus for this project was “New Approaches to HSCT Multidisciplinary Design and Optimization”. The successful development of a capable and economically viable high speed civil transport (HSCT) is perhaps one of the most challenging tasks in aeronautics. At its heart it is fundamentally the design of a complex engineered system that has significant societal,

environmental and political impacts. As such it presents a formidable challenge to all areas of aeronautics, and it is therefore a particularly appropriate subject for research in multidisciplinary design and optimization (MDO). In fact, it is starkly clear that without the availability of powerful and versatile multidisciplinary design, analysis and optimization methods, the design, construction and operation of an HSCT simply cannot be achieved. The recent termination of the NASA High Speed Research (HSR) was partially based on the lack of this capability as Boeing deemed the risk to be too high to make a program launch decision for an HSCT in the 2005 – 2006 timeframe. This project focused on the development and evaluation of MDO methods that, not only developed the basic methods but also to apply them to relevant examples from the NASA HSR R&D effort.

1. INTRODUCTION

Multidisciplinary design optimization, or MDO, addresses the considerable challenge of concurrently incorporating analysis models and design parameters from several different discipline areas into a design synthesis process implemented using powerful decision-support tools. Aerospace systems are inherently multidisciplinary in nature, and therefore MDO has been a key part of the design process from the beginning. However, it has been only in the last two decades that the problem complexities have risen well beyond the human abilities of the individual designer or the traditional design team. As a result, new emphasis has been placed on the development of powerful, flexible and robust MDO methods.

As illustrated in Figure 2 below, the initial efforts towards MDO focused on specific disciplinary interactions that were growing troublesome to handle or that had immediate and profound impact on the design process. While there are still significant challenges in these areas, the problem addressed in the present grant research involved the development of MDO methods to handle aerospace vehicle synthesis and sizing problems at the conceptual/preliminary phases of design

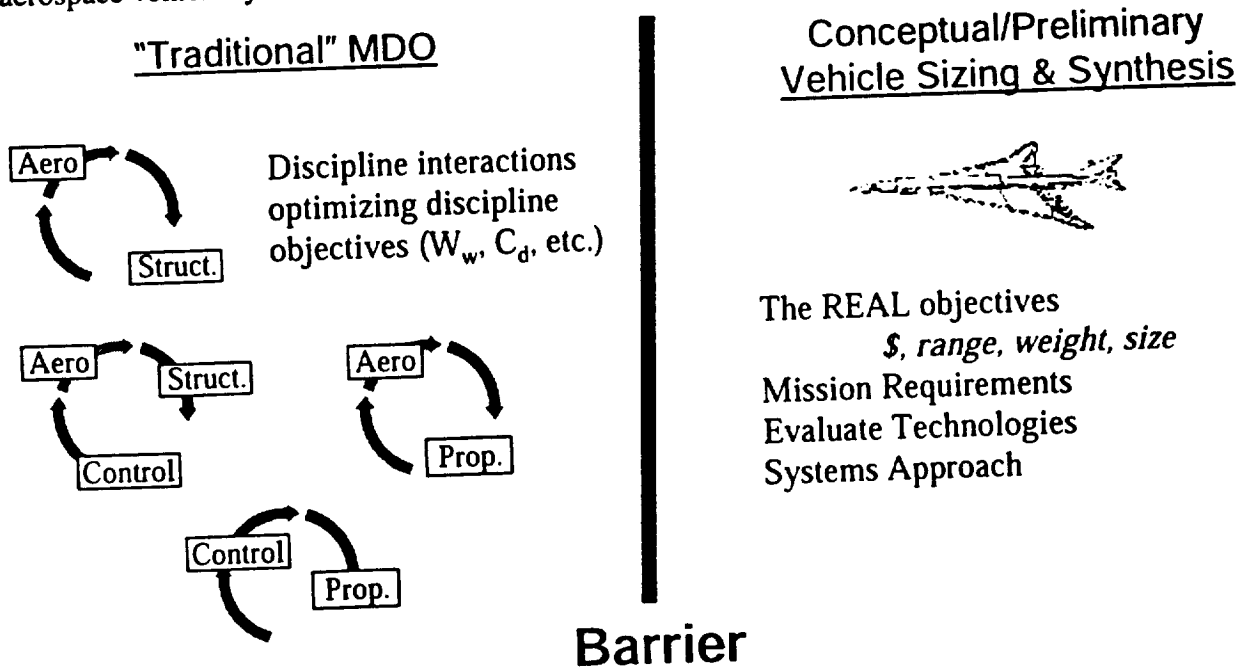


Figure 2. Grant Research Objectives Contrasted to Traditional MDO

The research involved a planned three year effort that was extended (at no additional cost) to four years and was aimed first at the description of the HSCT MDO problem, next the development of MDO methods for the solution of the problem, and finally the implementation of a solution to a significant portion of the problem. These phases are illustrated in Figure 3 where the fourth year extension has not been shown for simplicity.

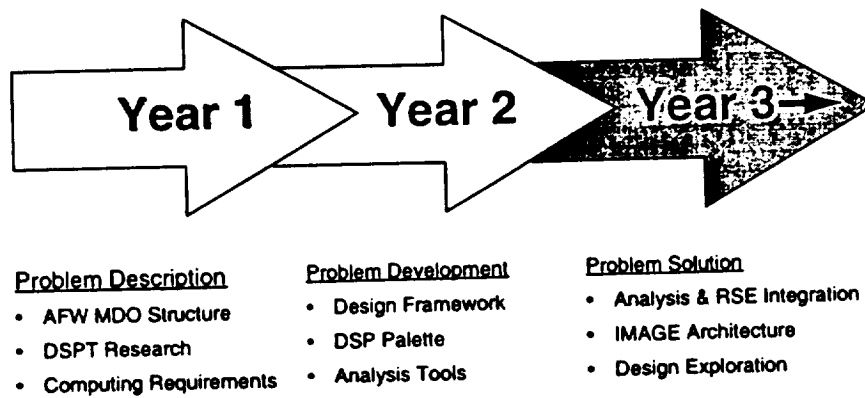


Figure 3. Three Year Task Schedule

The Year 1 effort focused on identification of a specific (and academically “tractable”) portion of the broader HSCT design problem. The initial attention was on the HSCT wing design including the product and process development aspects, but the focus shifted towards the multidisciplinary effort to handle the aeroelastic design of the wing and more specifically the case of an “active aeroelastic wing” (referred to as AAW for “active aeroelastic wing” or AFW for “active flexible wing”). Year 1 was also spent on adaptation and development of basic decision support methods to the problem and on the development of computing requirements for a practical system. The Year 2 effort involved the further development of the wing design framework, the development of specific classes of decision support problems (DSP palettes), and the identification and development of specific analysis tools. The Year 3 involved incorporation of robust design simulation methods involving the use of response surface equations (RSEs) to bring high-fidelity, discipline specific analysis and modeling methods forward into conceptual design studies from their more traditional places in subsystem level preliminary design efforts. The methods and tools were then tested and evaluated in sample MDO studies using the IMAGE design computing architecture.

The MDO methodology utilized is illustrated in Figure 4 as a hierarchical system decomposition which summarizes the problem approach. The complex problem of finding good designs for a flexible HSCT wing is based on the combined (and generally conflicting) objectives of minimum cost and maximum performance. The solution of this problem requires the combined analysis capabilities from the aerodynamics, structures, and controls disciplines. In addition, the simulation is multi-leveled, with objectives calculated at the system level through sizing and synthesis but with most of the design parameters distributed in subsystem level disciplines. The contributing analyses introduced through response surface equations allow a designer to perform tradeoffs in terms of the size of the design space searched and complexity of the tools used. The left half flow in Figure 4 illustrates the General Problem Solution Process following the DSPT. It also illustrates how the Sub-System Objectives are related to System Goals through the use of RSEs. The right hand flow in Figure 4 illustrates how this process was implemented for an aeroelastic wing design implementation. These MDO methodologies were coordinated and implemented in an MDO infrastructure and integration project which was initially identified as the Integrated Design Engineering Simulator (IDES) but later came to be known as DREAMS (Developing Robust Engineering Analysis Models and Specifications). This work resulted in the development of an open computing infrastructure that facilitates the design of complex engineering systems. The infrastructure was built on IMAGE (Intelligent Multidisciplinary Aircraft Generation Environment). The remainder of this report will provide more detail on the MDO methodology developed, accomplishments achieved, and a summary. The annual reports

for Years 1, 2, and 3 are included in Appendices B, C, and D, respectively, and a CDROM listing the grant publications along with electronic copies of most of them is included as Appendix E.

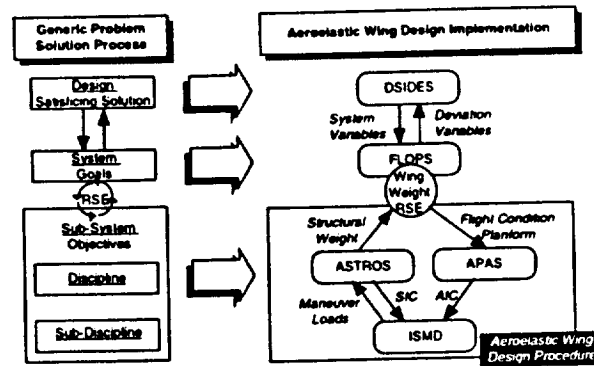


Figure 4. Hierarchical System Decomposition

A parallel effort, the NASA Multidisciplinary Design and Analysis (MDA) Fellowship Program, was leveraged by bringing additional participants into the research, as well as more industry participation and dissemination of results through annual review presentations to industry and government experts.

2. MDO METHODOLOGY

A drawback of using complex models (CFD, FEM, etc.) and complex tools during the research of new approaches to design is that the resources and time are often not available to synthesize more than merely a handful of different point designs. As a more desirable avenue for exploring new approaches to MDO, this project developed an Integrated Design Engineering Simulator (IDES, later called DREAMS/IMAGE) for executing the integrated Aero-Structures-Control methodology for the multidisciplinary design and optimization of an HSCT wing, as illustrated in Figure 4. A synopsis of the IDES method flow is:

- Use of the Decision Support Problem Technique (DSPT) for a HSCT Wing using a satisficing approach which includes identification of goals, deviation variables, and design variables
- Identification of required analysis/simulation tools
- Identification of information exchange between aero-structure-control modules
- Set up the Design of Experiment (DOE) for required system responses
- Run cases and perform Analysis of Variance (ANOVA) using simplified analytical tools and models in order to illustrate the procedure
- Develop RSEs from simulation results for use in preliminary IDES demonstration
- Implement aero-structure-controls integrated tool in IMAGE, with RSEs as agents
- Robust Design studies using RSEs integrated with FLOPS for a point design solution

Through the use of response surfaces, analysis-oriented methods are incorporated into IDES requiring only a one time investment for a given class of vehicles. Further, increased design

freedom and knowledge as well as reduced cycle time at the conceptual level make the resulting analysis portion of IDES more amenable to implementation in IMAGE, the computational infrastructure in which IDES is completed.

2.1 HSCT Approaches

Wing aeroelasticity and the calculation of flutter during transonic flight has been the “long pole in the tent” for the development of supersonic aircraft. During the Super-Sonic Transport (SST) development of the 1960s and early 1970s aeroelastic calculation of flutter for closing the loop with design was left open – to be resolved during prototype development. The same can be true to some extent for the recently terminated NASA/industry HSR program. As a result, this particular aspect of the HSCT design problem was the focus for the grant research and was the subject for the methodology evaluation. Thus it can be seen that an appropriate grand challenge was being tackled.

This particular problem presents the classical MDO challenge to designers working at the conceptual level: how to incorporate key multidisciplinary information and knowledge that is usually not available this early in the design process due to its dependence on higher fidelity models, databases and analysis tools. For example, wing aeroelasticity studies and transonic flutter calculations require much more detailed (higher fidelity) structural and aerodynamic models than are typically available at the conceptual phase of design. Yet it is well understood that it is at this early stage when these complex problems can be most effectively and economically addressed.

The new MDO approaches for HSCT wing design developed under the grant directly addressed the challenge of providing higher fidelity design models at the earliest stages (e.g., conceptual) of the design process. A methodology involving the application of response surface equations (RSE's; also referred to as “response surface method” or RSM) was developed and successfully applied to this problem. Rather than dealing directly with a high fidelity analysis requiring detailed system specifications not typically available at the conceptual design phase, the general characteristics of the analysis were represented by much simpler multidimensional polynomials (typically no greater than second degree) that define the “response surface” for the particular high fidelity analysis. This accomplished two important goals: (a) adequate representation of the physics of the problem under study, and (b) representation of the results in a form simple enough for use in conceptual phase studies. RSE's are certainly not new and others have tried with varying degrees of success to apply them in similar situations. However, the success in the present application was derived in no small part from the development of powerful and statistically accountable ways to generate the needed RSE's and to re-generate them when necessary to extend the design variable space. The key insight was to base the generation of the RSE's on a classical design of experiments (DOE) approach to vastly simplify the combinatorial explosion that results from trying to use more than a dozen or so design variables.

The initial RSM applications were to the analysis of HSCT economics but the grant research has extended the applications to aerodynamics, structural analysis and controls as necessary to address the wing aeroelasticity and transonic flutter design, including the potential application to active flexible wing (AFW) technologies. Figure 4 above summarizes the basic HSCT wing application while Figure 5 below illustrates the extension to the AFW in which the wing aeroelastic effects are actually used to advantage (rather than avoided) in the conceptual level design process for an HSCT application. The HSCT aeroelastic wing design method used in conjunction with the DOE/RSM is described in detail in Ref. 8, the Year 3 final report (Appendix D) and a recent doctoral thesis [11]. The problem addresses a finite-element based

structural optimization of a wing box under aerodynamic loads that is subjected to stress and flutter constraints. The wing is represented by a varying complexity spar and rib model and utilizes multiple shape functions for distribution of design parameters. A maneuver load program, called Integrated Structure/Maneuver Design (ISMD), provides for the computation of static external loads. The key objective of the wing design procedure is to balance the desire for a parametric procedure and a desire for increased analysis accuracy.

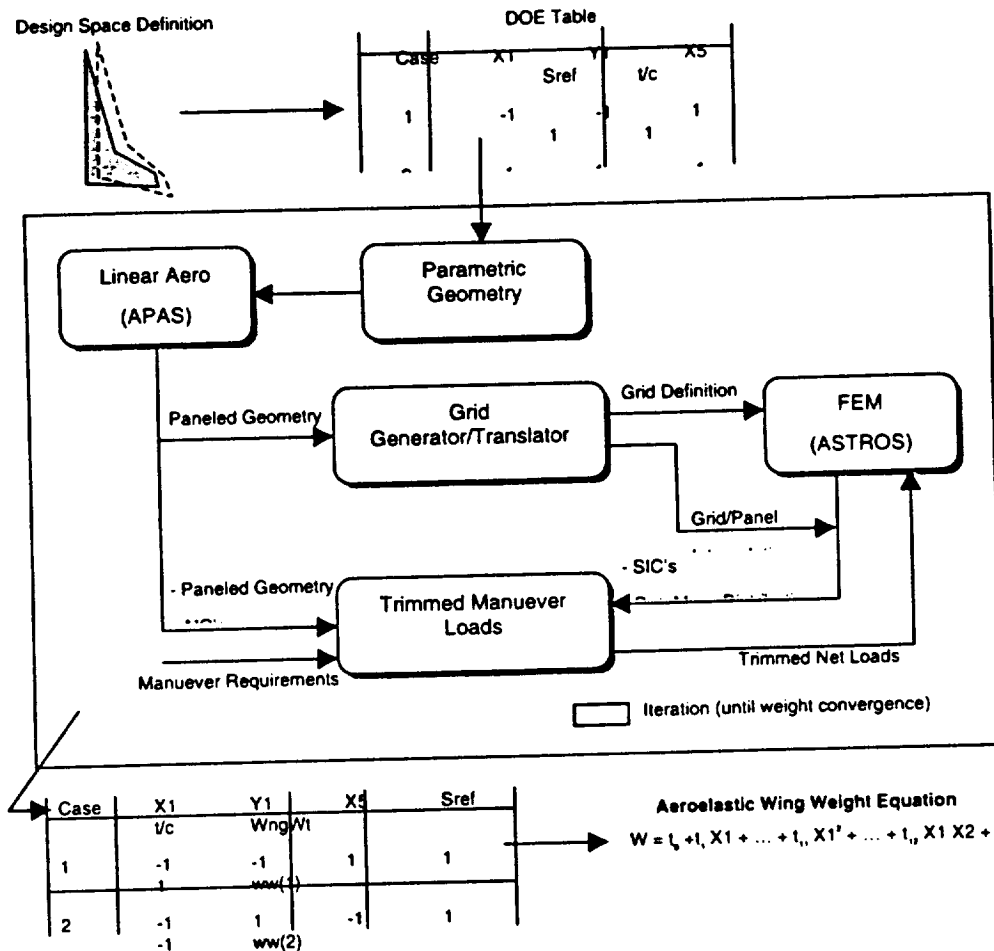


Figure 5. RSM/DOE Application to the AFW

Taken alone, the RSM only addresses the modeling of higher fidelity analyses at the conceptual level. Even with the availability of this new approach, one is still left with substantial uncertainty in the fundamental design data itself. For example, costs such as fuel or manufacturing, as well as projections of new technology availability are subject to considerable uncertainty, so that simply using purely deterministic values in an RSM to model a higher fidelity analysis may not be justifiable at the conceptual phase. To address this issue, a Robust Design Synthesis (RDS) approach was developed and applied to the HSCT conceptual design problem. The basic approach involved the incorporation of stochastic models for the design variables and design parameters and the development of tools for their propagation through the RSE's generated for the particular design space under consideration. The initial effort focused on basic Monte Carlo approaches to this problem but subsequent development has pursued the use of semi-analytical methods and so-called fast probability integration methods. The

fundamental developments in robust design methodologies are described in more detail in the following section.

2.2 Decision Support Methods

The basic HSCT wing design methodology outlined in the previous section addressed the challenge of moving higher fidelity design models and analysis tools forward into the conceptual and preliminary design phases of the design timeline and of handling the fundamental uncertainty inherent in the system parameters and design variables. This section summarizes the research effort to develop decision support methods to allow design decisions to be made in this environment with due account given to the level of fidelity as well as to the stochastic nature of the models and information.

The IDES/DREAMS methodology is based on the Decision Support Problem Technique (DSPT) in which the design process is organized based on the types of decisions which are being made and the domain-dependent information which is available to make those decisions. Within the DSPT, two principal types of decisions are available to a designer - selection decisions [56] and compromise decisions [39]. Each of these types of decisions is accomplished within the framework of a Decision Support Problem or DSP. Figure 6 below illustrates the compromise DSP in the context of the HSCT wing design problem under study. The compromise Decision Support Problem and the DSIDES software which implements it form the foundation for design exploration within this environment.

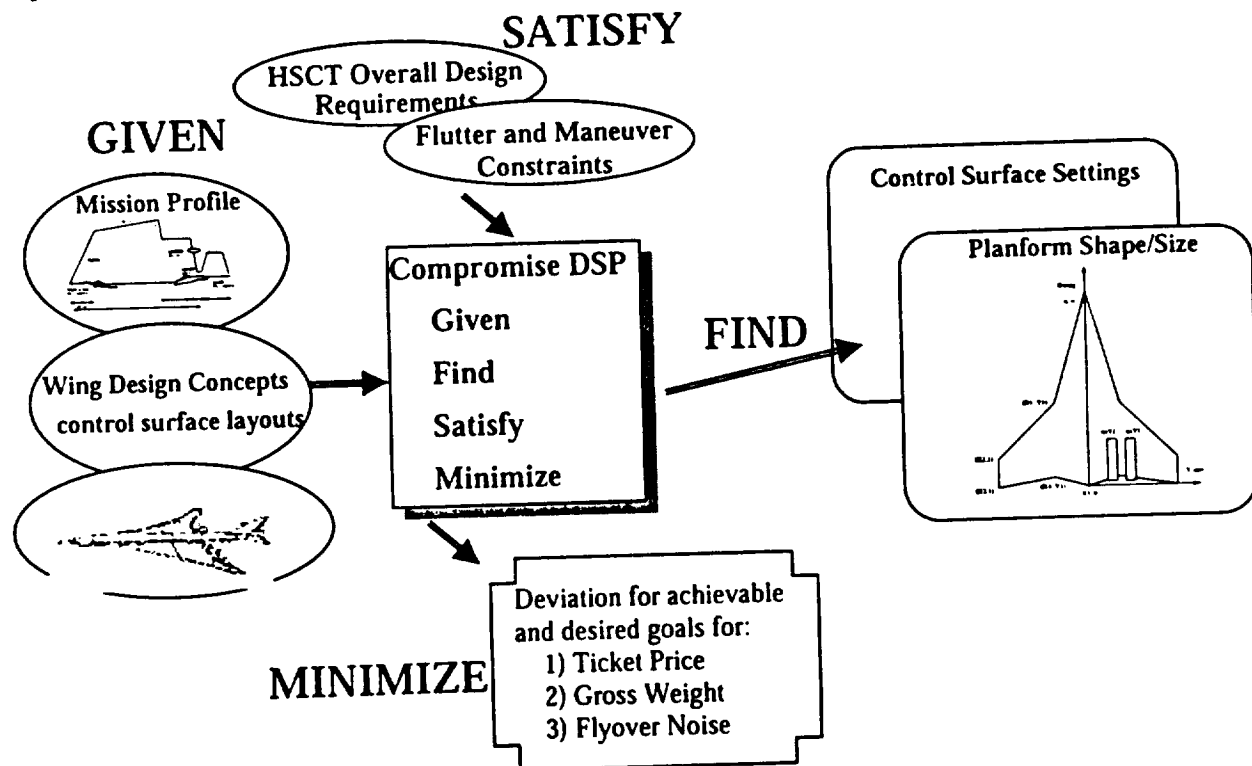


Figure 6. Compromise Decision Support Problem for HSCT Wing Design Problem

In the initial DSP application, the compromise DSP was used as the foundation for the development of a Robust Concept Exploration Method (RCEM) to facilitate the quick evaluation

of design alternatives and the generation of top-level specifications with quality considerations in the early stages of design of a complex system [1,2]. The RCEM was implemented by integrating several metrics and tools including Taguchi's robust design, Suh's independence axiom, the design of experiments and the response surface methodology into one mathematical construct - the compromise Decision Support Problem. The RCEM was demonstrated in the context of the design of an integrated HSCT airframe/propulsion subsystem [2,8]. The RCEM was then used to develop ranged sets of specifications which are common and good for a family of general aviation aircraft. In addition to focusing on the inclusion of robustness in design, the research addressed methods for increasing efficiency, increasing design knowledge and maintaining design freedom during the early stages of design for open engineering systems. It also dealt with methods for modeling design uncertainty in design formulations and on methods for prioritizing design objectives [64,65].

In complex system decomposition, subsystems may not be isolated, self-supporting entities. Constraints, goals and design variables may be shared between entities, however, full communication and cooperation often does not exist. The information may be incomplete, or one subsystem may dominate the design. Game theory was applied to the DSP involving the design of two coupled subsystems, one of which dominates the design process [37,44,45]. A conceptual framework for the application of game theory in complex systems design was developed and applied initially to the multidisciplinary design of a subsonic passenger transport aircraft; Figure 7 illustrates this approach. This research also led to development of an algorithm for solving mathematical models involving nonlinear functions of both discrete and continuous design variables [41,46].

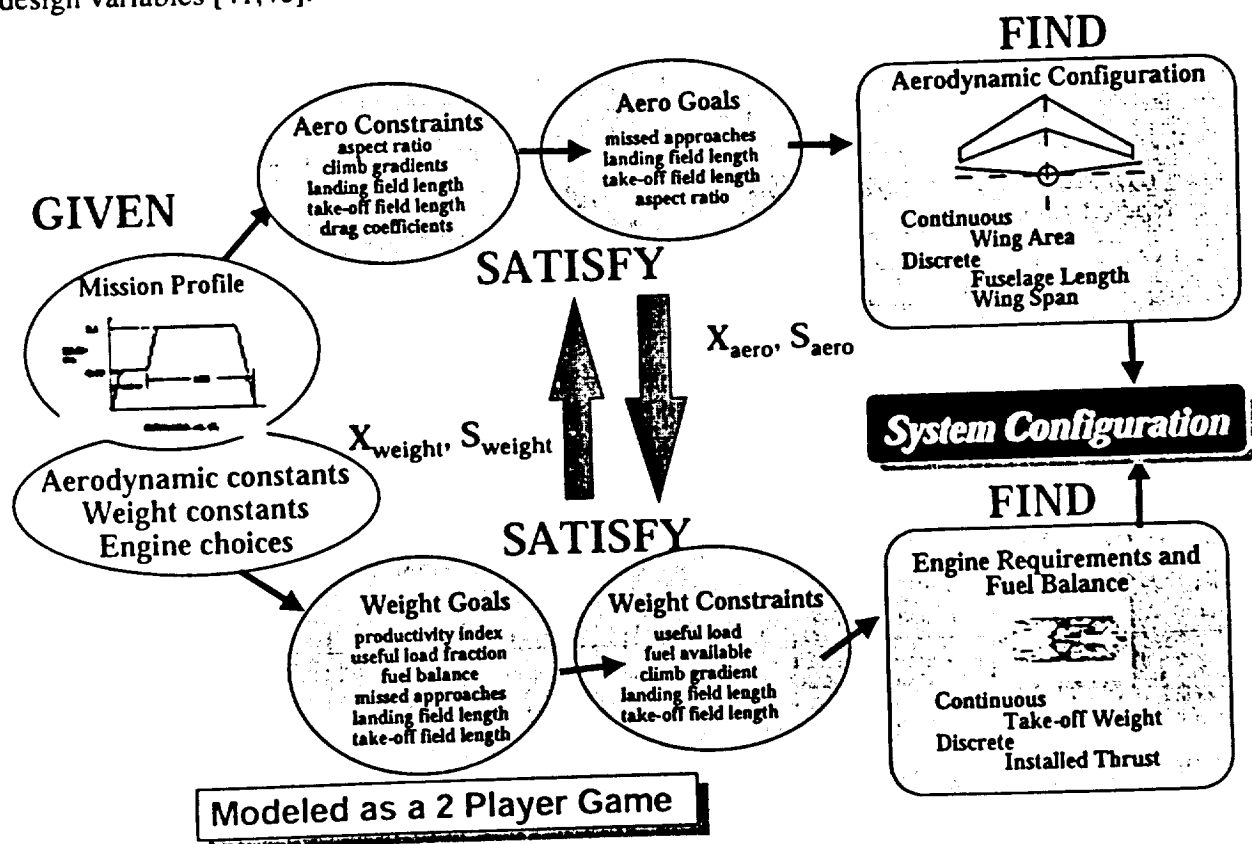


Figure 7. Alternative Decision Strategy: Game Theory

Complex systems usually involve an extensive hierarchical structure and this can be used to advantage in the decision support problem formulation. A hierarchical robust preliminary design exploration method was developed to facilitate concurrent system and subsystem design exploitation, and specifically for the concurrent generation of robust system and subsystem specifications for the preliminary design of multilevel, multi-objective, large-scale complex systems [34]. This method was developed through the integration and expansion of current design techniques including:

- hierarchical partitioning and modeling techniques for partitioning large-scale complex systems into more tractable parts and allowing integration of sub-problems for system synthesis [34];
- statistical experimentation and approximation techniques for increasing both the efficiency and the comprehensiveness of preliminary design exploration [35], and
- noise modeling techniques for implementing robust preliminary design when approximate models are employed [6,7].

These techniques were developed with a case study performed with Allison Engines/Rolls Royce Aerospace and are based on an existing engine designed for midsize commercial, regional business jets. The solutions obtained are similar to the design of the existing commercial engineer, but are better with respect to many of the requirements [34].

Additional supporting research provided a method for coupling objectives related to technical and economic efficiency in an environment involving the simultaneous consideration of multiple objectives, multilevel decisions and uncertainty [48]. This work further compared a single objective model with methods founded on the compromise Decision Support Problem [56, 77, 78].

2.3 Information Management in MDO

During the course of implementing this design scenario in DREAMS/IMAGE, the need to have a well defined data model became evident. In addition, research has shown that advances in the aircraft technologies have resulted in a commensurate increase in the amount of data required to define a design during the conceptual stages [28]. Conceptual design requires a tight multidisciplinary effort requiring large amounts of data exchange. In order to effectively implement the new MDO design processes described above, it is crucial that a top-down data management design structure be in place in the early phases of the design. This structure must provide consistency in data format and allow ease of data exchange between the various disciplines involved in the design process (Figure 8). In the conceptual design phase, consideration must be given to the changing structure of the of the database as the product design evolves. Current database design approaches are typically limited to the detailed design phase where the data organization is fixed and quite inflexible.

The data modeling problem is encountered for both design product and process models. Grant research investigated the use of IDEF0 structures for representing a design (Figure 9) and the use of these diagrams was extended to the use of design Palettes as illustrated for the AFW problem.

A data model is also required for the product information. Figure 10 shows an IDEF1X model for typical aircraft components. In this example, an aircraft configuration is made up of the components engine, fuselage, gear, inlet, nozzle, canard, horizontal, vertical, and wing. This

type of data model is utilized within the IMAGE architecture. An expansion of this data model using EXPRES to provide an object oriented perspective was also carried out [31] and showed some of the assets and liabilities of such models. It was concluded that the relational model was often sufficient for the early design area but that the object model had more flexibility for expanding the data model as the design evolves. The data modeling approach was also investigated [9,10] as a way of identifying and tracking the impact of local design changes on overall system design. The data model provides a system level view and appeared useful in tracking the propagation of change throughout a system.

In view of the massive computational requirements in MDO, a study was initiated to assess the potential of parallel computers to speed up computations. The focus was on algorithms associated with crash dynamics. The investigation looked at both non-linear structural dynamic computations typical of DYNA3D [71] and those aspects contained in the contact computations required in crash analysis [33]. The results in [71] gave very encouraging results and showed that significant improvement in performance could be achieved for nonlinear dynamic computations.

For the complex contact algorithms contained within source crash analysis, the results showed that by modifying key segments of the contact algorithm, improvements in speed were also achievable but not as dramatic for the other portions of the nonlinear dynamic analysis. In general, the results clearly show that parallel computers can be a significant aide in speeding up MDO computations and should be used on the major computationally intensive algorithms.

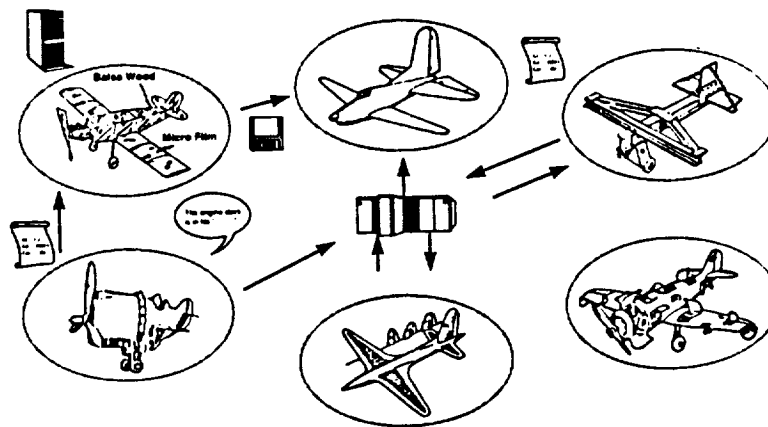
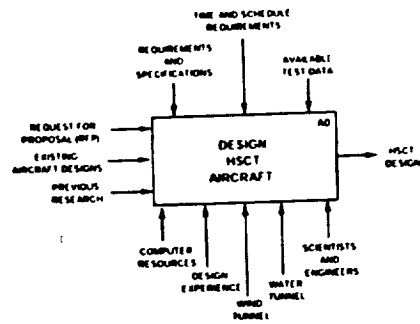
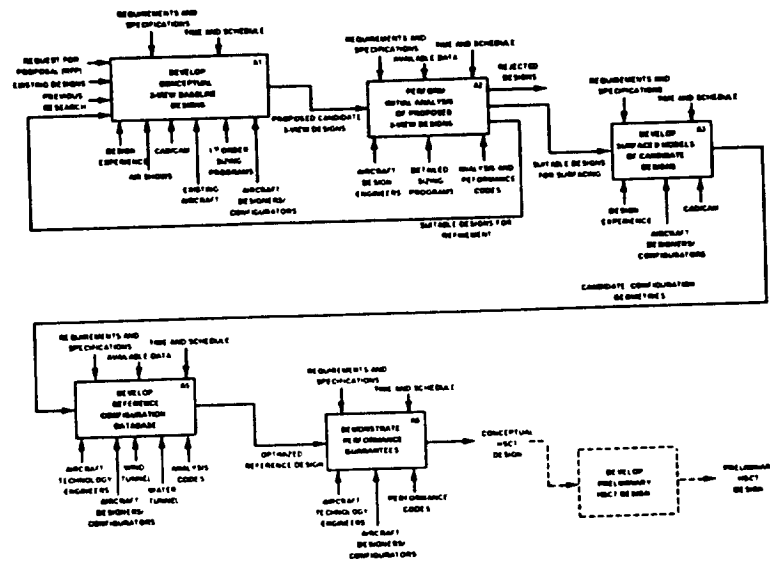


Figure 8. The Data Management Problem



(a) IDEF0 - Level 0



(b) IDEF0 - Level 1.

Figure 9. IDEF0 Diagrams.

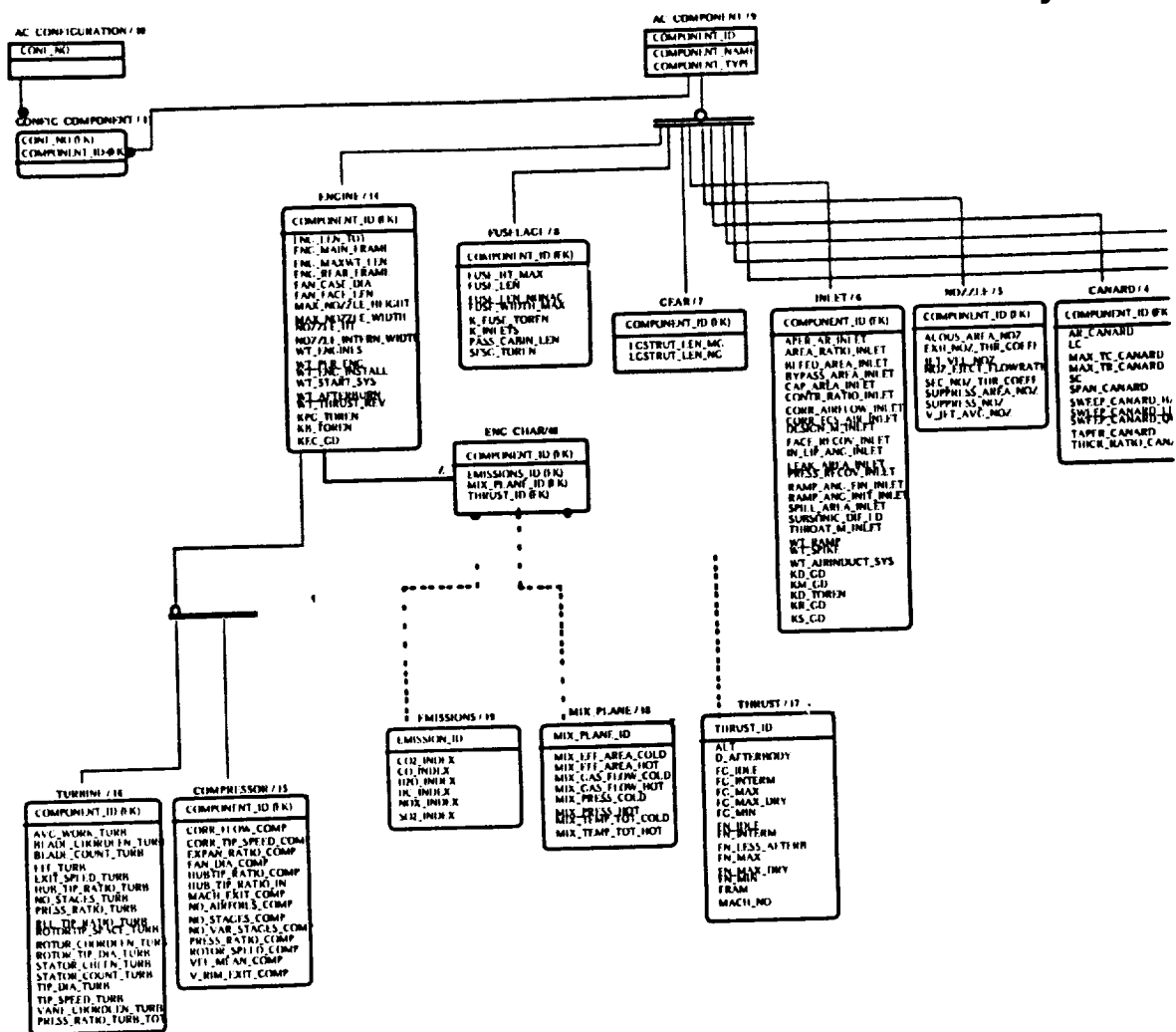


Figure 10. IDEF1X diagram of aircraft components.

2.4 MDO Computational Frameworks

The new MDO methodologies developed in the grant were implemented in an MDO *framework and integration* project that was also supported by NASA GSRP funding. This work was initially identified as the Integrated Design Engineering Simulator (IDES), but it ultimately was identified by the name, DREAMS [25], an acronym for “Designing Robust Engineering Analysis Models and Specifications.” Much of the computational architecture development was pursued under GSRP funding with project name, IMAGE (Intelligent Multidisciplinary Aircraft Generation Environment) [16]. However, the guidance for much of this was based on the requirements established by DREAMS to accommodate the new MDO approaches being developed under the grant. Additional specifications were derived from related projects such as FIDO (at NASA LaRC) and ASOP (at Rockwell).

The computational and information environment was designed and constructed to provide a framework for consistently applying a general decision-based design methodology within an integrated computing environment across the design timeline for open engineering systems. It is

based around an agent integration technology and results have demonstrated the feasibility in situations of practical complexity level [17-20]. A distributed, object-oriented database definition with dynamic schema editing was also demonstrated.

The infrastructure was designed to support the DREAMS methodology by incorporating:

- a design partitioning process;
- a mechanism for solving the resulting design sub-problems; and
- a design information model;

and by supporting:

- information generation in context for informed decision-making;
- efficient and cost-effective application of design resources; and
- geographically distributed design activities.

Figure 11 below shows the basic approach in a schematic form, and it refers to the following specific functional capabilities incorporated in the system:

- *Design Activities* in which a designer partitions a problem into activities for solution; this also provides for comprehensive information management;
- *Available Assets* which include a variety of design resources (e.g., programs) that provide aid in the generation of design knowledge; resources may include performance simulation codes, object-oriented databases, CAD packages, etc.;
- *Agent Collaboration* as implemented with a generic toolkit that allows resources to be incorporated into the design infrastructure with minimal effort by the engineering developers; the incorporation of a "model" (which describes precisely what an agent is capable of doing or providing and how it is accomplished) within the toolkit allows for knowledge to be generated in context allowing a designer to interrogate knowledge for the who, what, where, when, and how the information was created.
- *Computing Architecture* which includes components that are required for objects to operate in a distributed, homogeneous computing environment are included in an underlying infrastructure.

The computational framework is considered *open* because it provides freedom for a designer to model both processes and information as required at a particular point in a design's timeline. This was accomplished through an information model which incorporated schema evolution to capture time-dependent product and process characteristics at varying degrees of accuracy and fidelity. As a result, product descriptions can be modified as fidelity increases. For example, in the case of the HSCT wing design application considered in this project, an initial product description was based on parametric components. During finite element analysis, a more detailed model was required that included node and member definitions. Both of these representations coexisted in the information model. Moreover, specific instances (e.g. values) were accumulated for decision-making and optimization.

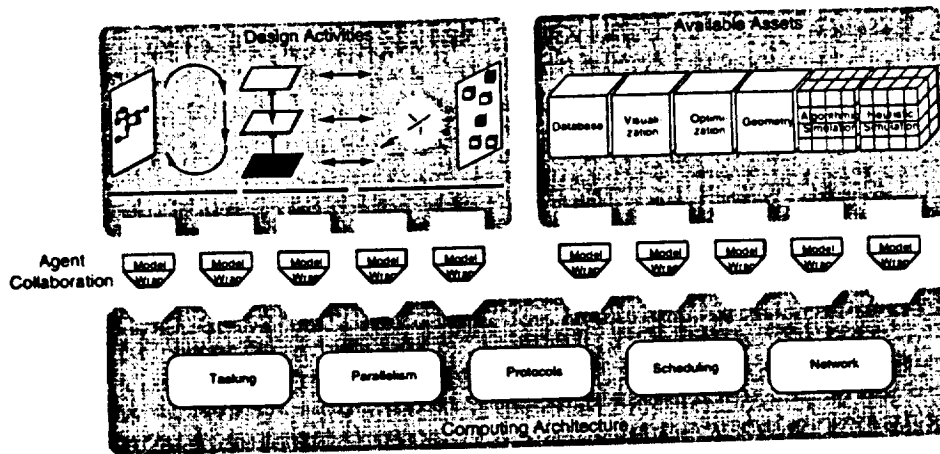


Figure 11. Infrastructure

The computational framework was demonstrated in several different HSCT wing design studies during the third and fourth years of the grant. Based on evaluations of the framework performance as well as from user feedback, a number of refinements and improvements were incorporated (some beyond the scope or support of the grant research). Much of this focused on improving usability of the integration tools and on enhancements to the user interface. Continuing development is moving the framework from its heavy dependence on the Unix environment to a more open architecture incorporating emerging web technologies and a "lean server" technology. When used in a client-server approach, a lean server using the hypertext transport protocol (http) provides a much more simplified server-side interface to analysis codes and decision support tools. Ultimately, the architecture will migrate towards a web-based and largely platform-independent configuration with most of the user interface implemented using the hypertext markup language (html). A current evaluation version of the IMAGE framework is available for download from: <http://alpha.cad.gatech.edu/image/>.

3. ACCOMPLISHMENTS

Research accomplishments under grant support are extensive and wide-ranging as documented in the grant bibliography provided in Appendix A. Consistent with the multidisciplinary theme of the grant, the research team included faculty and students in both Aerospace Engineering and Mechanical Engineering at Georgia Tech along with industrial participation from Rockwell International and Lockheed Martin (see below). The objective as stated in the initial proposal and refined in subsequent work statements for each of the 3 years was to develop a new MDO approach to aerospace systems design and to apply it to the HSCT design problem. The research plan was outlined in Section 2 above in four primary areas and substantial achievements have been made in all the areas.

A new approach to MDO focusing on the conceptual (advanced or pre-) design and early preliminary design phases was developed under the first two tasks described above. The approach involved a combination of consistent refinement in the fidelity of the analysis models with the incorporation of decision support problem (DSP) techniques to synthesize form to meet functional requirements. Both deterministic and stochastic approaches were developed.

The remaining two tasks focused on the implementation of the new MDO methodologies and their evaluation when applied to the HSCT design problem outlined in the initial proposal. One area of research considered the development of parallel computing strategies to support MDO.

The second addressed the development of computational frameworks to support MDO across the enterprise.

3.1 Industry Interaction

Interaction with both industry and government laboratories was an essential feature of the grant activities. These organizations have taken leading roles in the HSCT research and development, particularly in the area of design methodology. As a result, a close interaction with both Rockwell International- North American Aircraft (now Boeing Seal-Beach) and Lockheed Martin Aeronautical Systems (Marietta) formed a key part of the grant research.

Rockwell International provided important information about their active flexible wing (AFW) technology. They also provided the ISMD computer code for the computation of static external loads. The information not only allowed more realistic situations to be studied with the IPPD methodology developed during the grant but it also provided a baseline with which to make design comparisons. A significant part of the interaction took place through a summer internship program with the students working under the direction of Bob Schwanz at Rockwell.

Lockheed Martin provided additional information on their HSCT design methodology and in particular on related manufacturing technologies. A focus of this interaction involved manufacturing information that allowed the research team to develop methods to incorporate more accurate manufacturing cost information in the IPPD process at the conceptual level. As with the Rockwell interactions, student internships were the focus of this interaction as well.

3.2 Research Personnel

The grant supported graduate research assistants and post doctoral students in both Aerospace Engineering (under the supervision of Prof's. Schrage and Craig) and in Mechanical Engineering (under the supervision of Prof's. Fulton and Mistree). Most of the students were supported for their MS degree programs and a portion of their doctoral programs. A unique feature of the grant structure in Aerospace Engineering was the deliberate effort to involve a true multidisciplinary team of students, and to this end several of the students were supervised by other faculty members. For example one student completed his doctoral thesis in aerodynamics while another completed his doctoral thesis in aeromechanics. Both worked concurrently on HSCT design methods. Students in Mechanical Engineering focused on complementary MDO design methods and database and parallel computational technologies which were applied to the HCST problem as well as to other applications.

Table 1, which was first shown in the Year 3 grant report, summarizes the overall effort in both chronological and task dimensions. The table includes both Graduate Research Assistants (GRA's) as well as Post Doctoral Fellows (post docs) as well as supervising faculty. Due to the interdisciplinary nature of the research, several of the GRA's and Post Docs were supported in part under more than one project. It should be pointed out that Prof. Dimitri Mavris joined the research team for the final 18 months in order to more fully develop the response surface equation and probabilistic methods.

Table 2 shows the current employment (when available) of the students supported as Graduate Research Assistants (GRA's) or post doctoral fellows in Aerospace Engineering and Mechanical Engineering. Often the post doc was a former GRA who was supported following graduation in order to further extend or apply the doctoral research.

Table 1. Personnel Involvement on Grant Research

	Year 1 Problem Definition	Year 2 Problem Development	Year 3 Problem Solution	Year 4 Evaluation/Validation
Students	Jason Har			
	Neil Hall			
	Suresh Kamman			
	Tamara Lucas			
	Jason Neuhaus			
	Jacques Virasak			
	Srinivas Vadde			
	Scott Zink			
	Dr. Carlos Cesnik			
	Dr. Wei Chen			
	Dr. Dan DeLaurens			
	Dr. Mark Hale			
	Dr. Jerry Higman			
	Dr. Patrick Koch			
	Dr. Jae-Moon Lee			
	Dr. Kemper Lewis			
	Dr. William Marx			
	Dr. Peter Röhl			
Faculty	Dr. Rolf Rysdyk			
	Dr. Timothy Simpson			
	Dr. Sang Synn			
	Dr. Fidencio Tapia			
	Dr. Daniel Schrage			
Industry	Dr. James Craig			
	Dr. Farrokh Mistree			
	Dr. Robert Fulton			
	Dr. Dimitri Mavris			
	Rockwell International			
	Lockheed Martin			
	Boeing			
	General Electric			
	Wright Laboratory			
	NASA Langley			

Table 2. Graduates and Employment

Name	MS	PhD	Employment
Abel, Reginald	Dec-93		Boeing CAC
Bhutani, Nipun			
Brewer, Jason	Sep-94		GE AC
Cesnik, Carlos	Dec-91	Jun-94	MIT (assistant professor)
Chen, Wei		Sep-95	Univ. of Illinois (assistant professor)
DeLaurentis, Dan	Sep-93	Dec-98	Georgia Tech
Hale, Mark		Aug-96	Georgia Tech
Hall, Neil	Jun-96		Electronic Commerce Resource Ctr
Har, Jason		Mar-98	
Higman, Jerry		Mar-96	Army Laboratory
Kannan, Suresh			<i>masters student</i>
Kock, Patrick	Sep-94	Mar-98	Engineous
Lee, Jae-Moon		Mar-99	Georgia Tech
Lewis, Kemperer		Jun-96	SUNY Buffalo (assistant professor)
Lucas, Tamara	Jun-95		Lockheed Martin
Melamed, Nahum			
Neuhaus, Jason	Sep-98		Lockheed Martin
Rohl, Peter	Jun-92	Jun-95	General Electric (CRD)
Rysdyk, Rolf		Dec-98	Georgia Tech
Simpson, Tim	Dec-95	Dec-98	Penn State (assistant professor)
Stephens, Eric	?	Sep-93	Insight Designs, Inc. (president)
Stettner, Martin	Mar-91	Sep-95	DASA
Synn, Sang		Jan-95	
Tapia, Fidencio	Dec-92	Jun-96	Professor (UNAM)
Vadde, Srinivasan	Jun-95		Siemens
Virasak, Jacques	Dec-93		Lord Corp.
Volovoi, Vitali		Mar-97	Georgia Tech
Zink, Scott			<i>doctoral student</i>

4. SUMMARY

New approaches to MDO have been developed and demonstrated during this project on a particularly challenging aeronautics problem – HSCT Aeroelastic Wing Design. To tackle this problem required the integration of resources and collaboration from three Georgia Tech laboratories: ASDL, SDL, and PPRL, along with close coordination and participation from industry. Its success can also be contributed to the close interaction and involvement of fellows from the NASA Multidisciplinary Analysis and Optimization (MAO) program, which was going on in parallel, and provided additional resources to work the very complex, multidisciplinary problem, along with the methods being developed. The development of the Integrated Design Engineering Simulator (IDES) and its initial demonstration is a necessary first step in transitioning the methods and tools developed to larger industrial sized problems of interest. It also provides a framework for the implementation and demonstration of the methodology developed as illustrated in Figure 12.

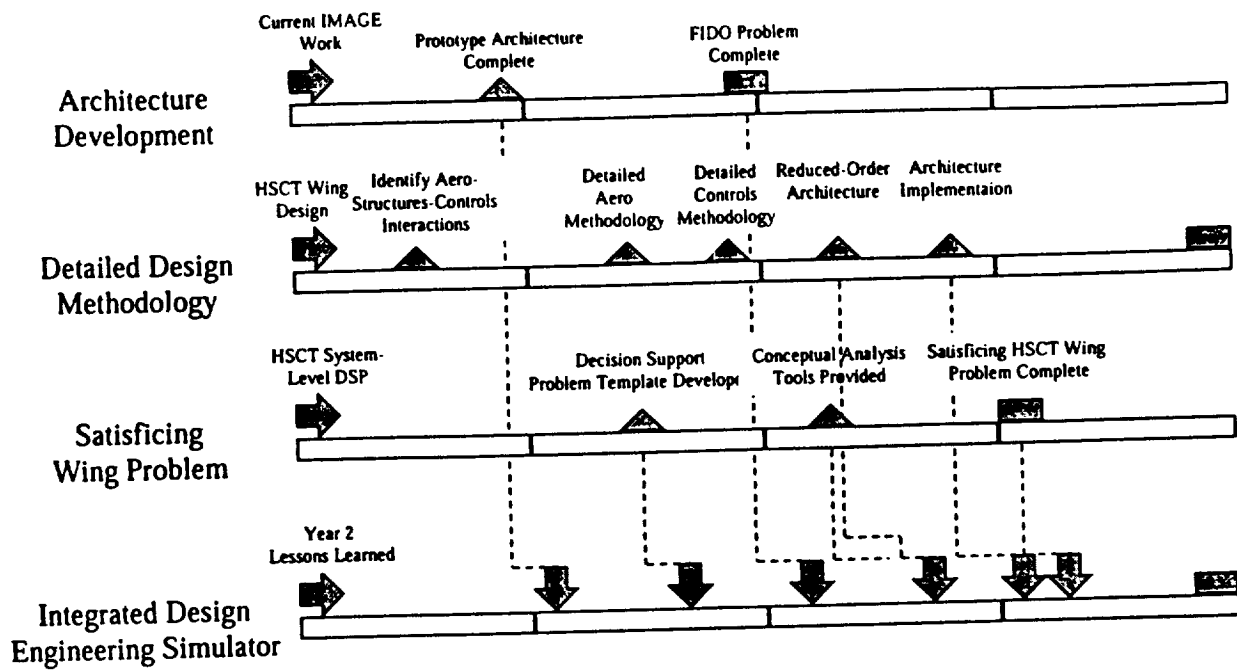


Figure 12. Demonstration Development

APPENDIX A. LIST OF PUBLICATIONS

The following publications were produced in whole or in part with funding from the NASA Grant. Unless otherwise noted, all these papers along with annual final reports are archived in Adobe PDF format on the CDROM accompanying this report (see Appendix E for details). The list below also serves as a reference list for this Final Report.

1. Chen, W., "A Robust Concept Exploration Method for Configuring Complex Systems," Ph.D. Dissertation, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA., 1995.
2. Chen, W., Allen, J.K., Mavris, D., Mistree, F., "A Concept Exploration Method for Determining Robust Top-Level Specifications," *Engineering Optimization*, vol. 26, pp. 137-158, 1996.
3. Chen, W., Simpson, T.W., Allen, J.K. and Mistree, F., "Using Design Capability Indices to Satisfy Ranged Sets of Design Requirements," *Advances in Design Automation*, (Dutta, D. Ed), New York: ASME 1996. ASME96-DETC/CAD-1090.
4. Chen, W., Tsui, K-L., Allen, J. K., Mistree, F., "Integration of Response Surface Method with the Compromise Decision Support Problem in Developing a General Robust Design Procedure," *Advances in Design Automation* (Azarm, S. et al, Eds.) New York: ASME, 1995, pp. 485-492. ASME DE-Vol. 82-2.
5. Chen, W., Allen, J.K. and Mistree, F., "System Configuration: Concurrent Subsystem Embodiment and System Synthesis," *ASME Journal of Mechanical Design*, vol. 118, no. 2, pp. 165-170, 1996.
6. Chen, W., Allen, J.K, Tsui, K-L and Mistree, F., "A Procedure for Robust Design: Minimizing Variations Caused by Noise Factors and Control Factors," *ASME Journal of Mechanical Design*, vol. 118, no. 4, pp.478-485, 1996.
7. Chen, W., Allen, J.K., Schrage, D.P. and Mistree, F., "Statistical Experimentation For Affordable Concurrent Design," *AIAA Journal*, vol. 35, no. 5, pp. 893-900, 1997.
8. Chen, W., Allen, J. K., and Mistree, F., "The Robust Concept Exploration Method for Enhancing Concurrent Systems Design", *Concurrent Engineering: Research and Applications*, vol. 5, no. 3, pp. 203-217, 1997.
9. Cohen, T., "A Data Approach to Tracking and Evaluating Engineering Changes", Ph.D. Thesis, Georgia Institute of Technology, 1997.
10. Cohen, T., Fulton, R.E. (1998) "A Data Approach to Tracking and Evaluating Engineering Changes", 1998 ASME Design Engineering Technical Conferences, Proceedings of DETC'98, Atlanta.
11. DeLaurentis, D., "A Probabilistic Approach to Aircraft Design Emphasizing Stability and Control Uncertainties," Ph.D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, November 1998.
12. DeLaurentis, D., Cesnik, C., Lee, J., Mavris, D., Schrage, D., "A New Approach to Integrated Wing Design in Conceptual Synthesis and Optimization," 6th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996. AIAA-96-4000.

13. DeLaurentis, D.A., Mavris, D.N., "An IPPD Approach to the Preliminary Design Optimization of an HSCT using Design of Experiments", 20th ICAS Congress, Sorrento, Italy, September 1996.
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15. Hale, M.A., "A Computing Infrastructure that Facilitates Integrated Product and Process Development from a Decision-Based Perspective," Ph.D. Thesis Proposal, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, January, 1995.
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19. Hale, M. A. and J. I. Craig, "Techniques for Integrating Computer Programs into Design Architectures," Sixth AIAA / NASA / USAF / ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996. AIAA-96-4166.
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21. Hale, M. A., "IMAGE: A Design Integration Framework Applied to the High Speed Civil Transport," HM301: First University/Industry Symposium on High Speed Civil Transport Vehicles, North Carolina State University, December 4-6, 1994.
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26. Hall, N., and Fulton, R.E., "A Relational Database Application to Multidisciplinary Conceptual Design for HSCT," (Submitted for the publication).

27. Hall, N., and R. Fulton, "A Relational Database Approach to a Multidisciplinary Conceptual Design for the HSCT," Georgia Institute of Technology, September, 1994.
28. Hall, Neil S. and Fulton, Robert E., "An Investigation of a Relational Database Approach to a Multidisciplinary Conceptual Design for the HSCT", 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, California, August 18-22, 1996, Paper Number 96-DETC/EIM-1425.
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38. Lewis, K. and Mistree, F., "On Developing a Taxonomy for Multidisciplinary Design Optimization: A Decision-Based Perspective," First World Congress of Structural and Multidisciplinary Optimization, Goslar, Germany. Paper number 118., 1995.
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53. Marx, W. J., Schrage, D. P., and Mavris, D. N., "An Application of Artificial Intelligence for Computer-Aided Design and Manufacturing," International Conference on Computational Engineering Science; Supercomputing in Multidisciplinary Analysis and Design, Mauna Lani, HI, July 30 - August 3, 1995. ICES-95-B6-3.
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63. Rohl, P.J., Schrage, D.P. and Mavris, D.N., "Combined Aerodynamic and Structural Optimization of a High-Speed Civil Transport Wing," 36th AIAA Structures, Dynamics, and Materials Conference, New Orleans, LA, April 1995, AIAA 95-1222.
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65. Simpson, T.W., "Development of a Design Process for Realizing Open engineering Systems," M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, August 1995.
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67. Synn, S.Y. and Fulton, R.E., "Practical Strategy for Concurrent Substructure Analysis," *Journal of Computers Structures*, vol.54, no.5, 1995.
68. Synn, S.Y. and Fulton, R.E., "The Concurrent Element Level Processing for Nonlinear Dynamic Analysis on a Massively Parallel Computer," Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, 1994.
69. Synn, S.Y. and Fulton, R.E., "The Prediction of Parallel Skyline Solver and It's Implementation For Large Scale Structural Analysis," Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, 1994 (also in *Journal of Computer Systems in Engineering*).
70. Synn, S.Y. and Fulton, R.E., "The Prediction of Parallel Skyline Solver and its Implementation for Large Scale Structural Analysis," Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, 1994, (Also, in *Journal of Computer Systems in Engineering*).
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78. Vadde, S., Allen, J.K., Lucas, T. and Mistree, F., "On Modeling Design Evolution Along a Design Time-Line," 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization - Panama City, September 7-9, 1994. AIAA-94-4313.
79. Vadde, S. and Mistree, F., "Design of a Shaft-Disk System: Modeling Interactions Between Design and Manufacture," AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, Washington, September 4-6, 1996, pp. 1546-1557. AIAA Paper Number 96-4162.

Workshops Supported by NASA Grant NGT 51102L:

- HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, December 1993.
- HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1994.
- HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1995.
- HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1996.

APPENDIX B: YEAR 1 REPORT

NEW APPROACHES TO MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

Summary of Progress to Date

September 26, 1994

D. P. Schrage, PI/PM
Aerospace Systems Design Laboratory
School of Aerospace Engineering

R. E. Fulton, co-PI
Parallel Processing Research Laboratory
School of Mechanical Engineering

J. I. Craig, co-PI
Aerospace Systems Design Laboratory
School of Aerospace Engineering

F. Mistree, co-PI
Systems Realization Laboratory
School of Mechanical Engineering

Rockwell International - North American Aircraft
Seal Beach, CA

Lockheed Aeronautical Systems Company
Marietta, GA

1. Review of Initial Contract Proposal

Georgia Tech has followed an open architecture approach to concurrent engineering whereby parallel product and process trades are used to supplement an explicit decision-making process. This Integrated Product and Process Development (IPPD) process is outlined in Figure 1. The multidisciplinary High Speed Civil Transport wing integration problem is being used as the GIT IPPD case study, see Figure 2. The problem will entail structural and aeroelastic optimization, including Rockwell Active Flexible Wing Technology. Emerging Lockheed lean aircraft manufacturing and advanced structures and materials developments will be incorporated as the problem is refined. The overall objective of the GIT proposal is to provide a mechanism for building and evaluating virtual designs of advanced aerospace vehicles to be used by interdisciplinary design teams. The Interdisciplinary Design Engineering Simulator (IDES) will merge IPPD methodologies with interdisciplinary analysis techniques and state-of-the-art computational technologies.

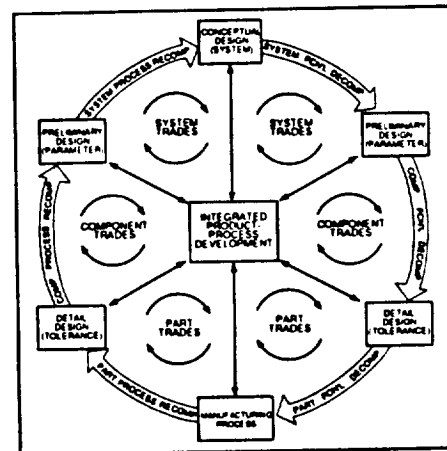


Figure 1. Integrated Product and Process Development (IPPD)

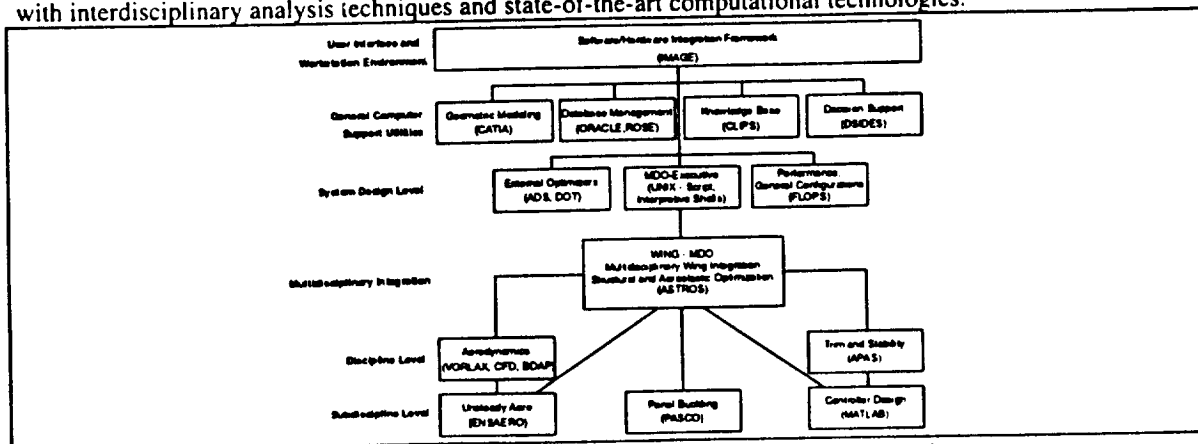


Figure 2. Georgia Tech HSCT Wing Design Project Organization

2. Year One Design Development

A new method for developing robust engineering analysis models and specifications was developed as the foundation of the Interdisciplinary Design Engineering Simulator (IDES). Formulated during the first years contract work, the method formalizes an approach for performing design analysis in order to obtain robust engineering specifications used during systematic decision-making. As shown in Figure 3, the method incorporates the designer's perspective through the *Decision Support Problem Technique* (DSP Technique) in which designer support problems are systematically *Formulated*, *Translated*, and *Evaluated*. Information management is provided throughout the decision-making process by using coherent design *Specifications*.

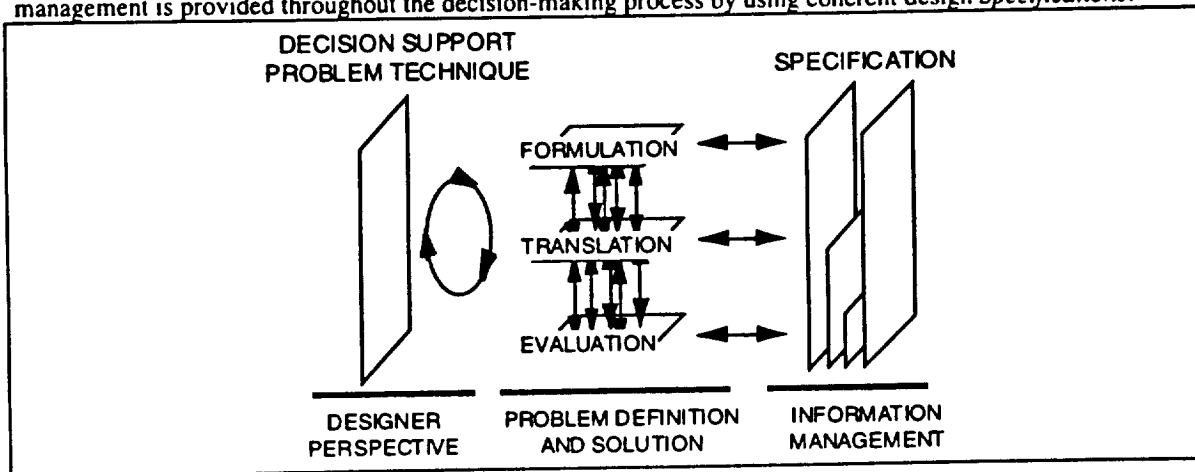


Figure 3. IDES Methodology

2.1 Designer Perspective

The Decision Support Problem Technique facilitates designing from a decision-based perspective and includes two phases: the meta-design phase, where the design process is designed and the actual design process where the product is designed by executing a number of *support problems*. Furthermore, a mechanism exists to provide the designer with a consistent mechanism for the formulation, translation, and evaluation of support problems. As seen in Figure 4, support problems are used throughout the design process. In Figure 4, "snapshots" at two points along a design timeline are shown. The underlying notion that is captured with the DSPT is to include many candidate designs during early stages of design, minimizing the deviation from "what I want" to "what I can have". After the "what if" questions have been investigated, the candidates can be narrowed to optimal solutions. The progression from *satisficing* solutions to an optimal solution expands the scope of traditional optimization methods and incorporates newer system sensitivity approaches.

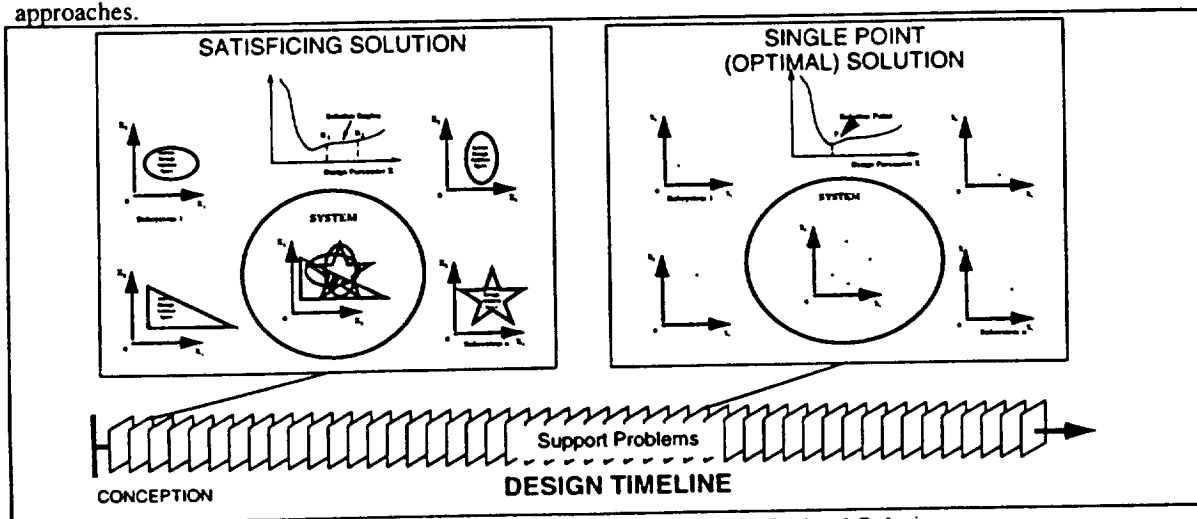


Figure 4. Movement from a Satisficing to an Optimal Solution

2.2 Problem Definition and Solution

Support problems are used throughout a design's life-cycle. The DSP technique is used to *Formulate* (compromise decision) support problems in which problem statements are structured linguistically. The linguistic (compromise decision) support problems are *Translated* into an equivalent form based upon known (mathematical) models. The support problems are *Evaluated* by coupling the (mathematical models) with analysis tools, organizing the solution process, and solving the (compromise decision) support problems. Figure 5 shows the compromise decision support problem development for the multidisciplinary wing integration IPPD case study. The wing manufacturing problem is another support problem that is being investigated.

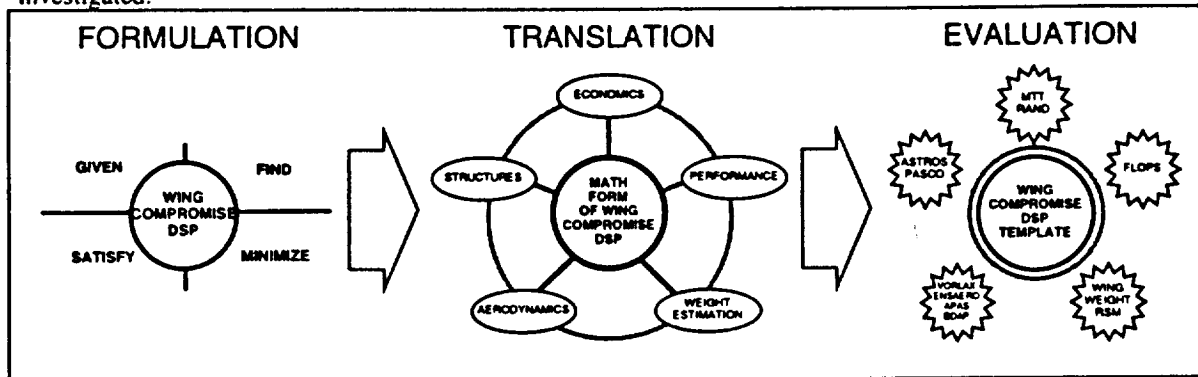


Figure 5. Multidisciplinary Wing Integration Support Problem Development

At the evaluation phase, the wing integration support problem template is a structured representation of Figure 2. Figure 6 outlines a partial analysis schedule that is required for solution of the support problem. Decision Support In the Design of Engineering Systems (DSIDES) is used to solve the support problem. An Intelligent Multidisciplinary Aircraft Generation Environment (IMAGE) addresses the semantics of the agent-client relationships required for cooperative problem solving.

2.3 Information Management

Information is categorized as either hierarchical or heterarchical. An information hierarchy is used for structured problem decomposition, storage/retrieval, and communication. The form-function-process-model relationship provides a coherent specification for quantifying the design space and Product model-Based Analytical Models (PBAM) provide a new representation of engineering analysis models. CALS, PDES, STEP, and EXPRESS are various data models employed for information storage and retrieval. Heterarchical information is equally important and represents information that cannot be categorized. Heterarchical information includes such things as local program variables and customer requirements.

Schemes for modular, distributed data management are being investigated. The schemes employ parallelized relational and object-oriented technologies that are capable of solving large, interdisciplinary design problems. The Laboratory Environment for the Generation, Evaluation, and Navigation of Design (LEGEND) provides a distributed design laboratory for the development and management of design specifications. In addition, guidance capabilities based on information content are being investigated.

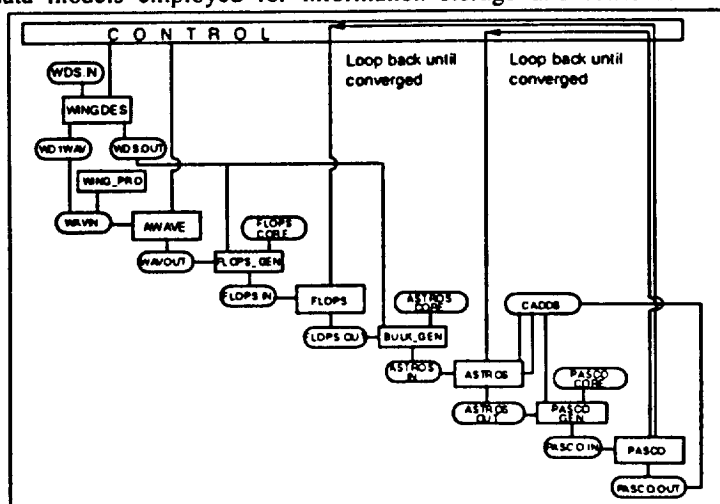


Figure 6. Partial Analysis Schedule Corresponding to Wing Compromise DSP Template

3. Year One Objectives and Results

The objective of the New Approaches to the HSCT Multidisciplinary Design and Optimization proposal is to provide the coherent methods and systematic tools necessary for the life-cycle design of advanced aerospace vehicle analysis and optimization. The program will result in the demonstration and development of an Interdisciplinary Design Engineering Simulator (IDES). The first year's efforts have predominately focused on a consistent methodology that supports life-cycle design issues. The resulting method allows for the development of robust engineering analysis models and specifications. The following table outlines the first year's objectives, expected significance, and results.

Objectives	Expected Significance	Results
1. Complete Development of the MDO Structure for the HSCT Wing Design to serve as the baseline process for including additional new approaches during subsequent years. The initial computing infrastructure will be composed of linked workstations and parallel computers.	1. Provides a demonstration of a new approach in the near term and will provide a common baseline for all involved researchers who are addressing new approaches. Will provide an early independent assessment of the benefits of AFW and High Lift Devices for the HSCT.	1. Formulation of a HSCT wing compromise decision support template. The template coincides with the systematic techniques employed in IDES for formulating, translating, and evaluating support problems.
2. Develop the Decision Support Problem technique (DSPT) for extension and implementation of the CE/IPPD Design Methodology.	2. Serves as the Meta-design phase for developing IDES.	2. Captured by incorporating the designer's perspective through the use of the DSPT in IDES.
3. Document the High Performance Computing Requirements for the baseline MDO Structure and identify the requirements for the IDES prototype.	3. Clearly documents a heterogeneous computer environment for the MDO environment and resources required for the IDES prototype.	3. Key design operators have been identified for the IDES architecture and will be highlighted in the Intelligent Multidisciplinary Aircraft Generation Environment (IMAGE) thesis proposal.

Key research areas have been identified in the development of the IDES methodology and are being investigated by a number of graduate students supported by this project and related projects. The following table highlights the topics being investigated by the students:

Topic	Researcher
RCEM - Robust Concept Exploration Method	Wei Chen
IMAGE - Intelligent Multidisciplinary Aircraft Generation Environment	Mark Hale
Information Management Strategies to Support Multidisciplinary Optimization Computations	Neil Hall
Application of Parallel Processing to Finite Element Systems	Jason Har
The Solution of Mixed Discrete/Continuous Systems in Non-Hierarchic, Multidisciplinary Design	Kemper Lewis
A Multilevel Decomposition Procedure for the Preliminary Wing Design of a High Speed Civil Transport Aircraft	Peter Röhl
Integrating Design and Manufacturing for the High Speed Civil Transport	William Marx
Guiding Decision Based Design Processes Through Management of Design Information Content	Srinivas Vadde

Attached to this review is a listing of supporting papers and presentations that have resulted from the first year's research efforts.

NEW APPROACHES TO MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

Presentations, Publications and Workshops

September 26, 1994

The following publications and workshops were done under the first year's research work:

PRESENTATIONS & PUBLICATIONS

- Hale, M. and J. Craig, "Preliminary Development of Agent Technologies for a Design Integration Framework," AIAA-94-4297, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Hall, N., and R. Fulton, "A Relational Database Approach to a Multidisciplinary Conceptual Design for the HSCT," Georgia Institute of Technology, September, 1994.
- Lewis, K., T. Lucas and F. Mistree, "A Decision-Based Approach for Developing Ranged Top-Level Aircraft Specifications: A Conceptual Exposition," AIAA-94-4304, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Marx, W., D. Schrage and D. Mavris, "Integrated Product Development for the Wing Structural Design of the High Speed Civil Transport," AIAA-94-4253, 5th AIAA/ NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Marx, W., D. Schrage and D. Mavris, "Integrated Design and Manufacturing for the High Speed Civil Transport," 19th ICAS Congress/AIAA Aircraft Systems Conference, Anaheim, CA, September, 1994.
- Mistree, F., K. Lewis and L. Stonis, "Selection in the Conceptual Design of Aircraft," AIAA-94-4382, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Röhl, P., D. Schrage and D. Mavris, "A Multilevel Wing Design Procedure Centered on the ASTROS Structural Optimization System," AIAA-94-4411, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Vadde, S., J. Allen, and F. Mistree, "On Modeling Design Evolution Along a Design Time-Line," AIAA-94-4313, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

WORKSHOPS

- HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, December 1993.
- HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1994.

APPENDIX C. YEAR 2 REPORT

NEW APPROACHES TO MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

Year 2 Progress Report NGT 51102L

October 1995

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School of Aerospace Engineering

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Parallel Processing Research Laboratory
School of Mechanical Engineering

J. I. Craig, co-PI
Aerospace Systems Design Laboratory
School of Aerospace Engineering

F. Mistree, co-PI
Systems Realization Laboratory
School of Mechanical Engineering

Rockwell International - North American Aircraft
Seal Beach, CA

Lockheed Aeronautical Systems Company
Marietta, GA

Year Two Objectives and Results

Research under the subject grant is being carried out in a jointly coordinated effort within three laboratories in the School of Aerospace Engineering and the George Woodruff School of Mechanical Engineering (see titles above). The objectives and results for Year 2 of the research program are summarized the table below. The "Objectives" and "Expected Significance" are taken directly from the Year 2 Proposal presented in October 1994, and "Results" summarize the what has been accomplished this year. A discussion of these results is provided in the following sections. A listing of papers, presentations and reports that acknowledge grant support, either in part or in whole, and that were prepared during this period is provided in an attachment.

Objectives	Expected Significance	Results
1. Develop and Document a Framework and Design Specification for the IDES using the HSCT wing optimization problem	1. Provides the structure and disciplines necessary to complete development of IDES addressing a relevant MDO problem	1. Disciplinary tools for the HSCT wing optimization problem are available, integrated in a multilevel analysis and optimization schedule.
2. Merge the MDO structure from Year One into the IDES Meta-design based on the Decision Support Problem Technique (DSPT).	2. Provides the initial IDES prototype for evaluation and identification of changes for incorporation into the final IDES design	2. The Intelligent Multidisciplinary Design Environment (IMAGE) is nearing completion. Agents for HSCT modeling are incorporated.
3. Define the High Performance Computing Requirements for the IDES Prototype and identify the requirements for the final IDES design..	3. Provides the requirements and documentation for the IDES heterogeneous computer environment and identifies required changes.	3. A dynamic, object-oriented data model was developed and implemented. Parallelization efforts progressed. Performance predictions for parallel solvers were developed.

Development of New Approaches:

Decision Support in MDO

A *robust concept exploration method* has been developed (Chen, 1995a). Robust concept exploration is facilitated by bringing rigorous analysis tools generally used in the later design stages into the early design stages for simulation and/or approximation. The integration and implementation of statistical methods and robust design techniques allows for efficient and effective exploration of different design concepts. Given overall design requirements, then, the Robust Concept Exploration Method is used to identify top-level (system level) design specifications with quality considerations. These specifications are then used for the preliminary design of major subsystems (subsystem embodiment). This approach to determining top-level specifications for airframe geometry and the propulsion system is demonstrated for the HSCT airframe configuration and propulsion system (Chen 1995a) and a general aviation aircraft (Simpson 1995a). Related publications include Chen 1995b,c.

We are laying the foundation for designing *open systems* using MDO (Simpson, 1995a). There are two aspects to designing an open engineering system. First, there is the product which is an open engineering system. Second, there is the process which is being used to design the product. Under the umbrella of the proposed Georgia Tech IPPD methodology a decision-based design methodology which embodies phases, events, tasks, and decisions is being developed to enhance openness in the design of engineering systems (Hale et al., 1995).

Problems in complex systems design are difficult to analyze and solve, and require methods to handle such issues as multilevel decomposition, mixed discrete/continuous models, and multiobjective and highly constrained design spaces. Specifically, we are working on developing a common lexicon for MDO, based on mapping the work of Balling/Sobieski and our decision-based approach to complex systems design (Lewis and Mistree, 1995a), identifying a ranged sets of top-level specifications (Lewis et al., 1995b), the solution and coordination of mixed discrete/continuous complex systems models (Lewis, 1996), and investigating both hierarchical and nonhierarchical decomposition schemes specifically along a design time-line (Lucas 1995a,b, Vadde 1995, 1994). Other publications include one dealing with multiattribute selection Mistree et al. 1994 and another dealing with design for manufacturing Simpson et al. 1995b.

MDO Methodology

Implementation of the multilevel wing optimization strategy developed in the first year effort resulted in a tool for multidisciplinary wing design, documented in Dr. Röhl's Ph.D. Thesis, which was used for optimal wing jig shape and aeroelastic tailoring studies in consideration of buckling constraints. The environment in which this tool was created is modular and flexible, thus open to the addition of further disciplinary modules. With this in mind, a framework for integrating methods and tools developed in this work with other disciplines (including contributions from Rockwell International) was established. This framework conceptually links analysis modules of Dr. Röhl's multilevel method with tools for aerodynamic and loads analysis. Rockwell's maneuver load program, ISMD, provides for the computation of structural loads. This framework provides the starting point for Year 3's goal of an integrated aero-structures-controls application in IDES.

A Process-Based Cost (PBC) model for the production cost of an HSCT wing (fabrication and assembly) has been developed and integrated into the top-down Aircraft Life-Cycle Cost (LCC) Analysis code, ALCCA. The resulting multi-level LCC model permits the generation of LCC profiles that are sensitive to alternative concepts, materials, and manufacturing processes of the HSCT.

Infrastructure for MDO:

Specific MDO methodologies developed in the present grant are coordinated in an MDO *infrastructure and integration* project that is also supported by NASA GSRP funding. This work was identified in the original proposal (and all subsequent to it) as the Integrated Design Engineering Simulator (IDES), but it is currently identified by the project name, DREAMS, which stands for "Designing Robust Engineering Analysis Models and Specifications." The bulk of the computational architecture development is being pursued under GSRP funding with project name, IMAGE (Intelligent Multidisciplinary Aircraft Generation Environment). However, the guidance for much of this architectural development is based on the requirements established by DREAMS to accommodate the new MDO approaches being developed under the grant. Additional specifications are being derived from related projects such as FIDO and ASOP. Recent publications (Hale 1994a-b, 1995a-d) listed at the end of this report highlight year 2 accomplishments in defining the information structures and the decision support process to be incorporated in this environment.

The computational and information environment is being designed and constructed to provide a method for consistently applying a decision-based design methodology within an integrated computing environment across the design timeline for open engineering systems. It is based around an agent integration technology and results to date have demonstrated the feasibility in situations of practical complexity level. A distributed, object-oriented database definition with dynamic schema editing has also been demonstrated.

The infrastructure is being designed to support the DREAMS methodology by incorporating:

- a design partitioning process;
- a mechanism for solving the resulting design sub-problems; and
- a design information model;

and by supporting:

- information generation in context for informed decision-making;
- efficient and cost-effective application of design resources; and
- geographically distributed design activities.

Figure 1 below shows the basic approach in a schematic form, and it refers to the following specific functional capabilities incorporated in the system:

- *Design Activities* in which a designer partitions a problem into activities for solution; this also provides for comprehensive information management;
- *Available Assets* which include a variety of design resources (e.g., programs) that provide aid in the generation of design knowledge; resources may include performance simulation codes, object-oriented databases, CAD packages, etc.;
- *Agent Collaboration* as implemented with a generic toolkit that allows resources to be incorporated into the design infrastructure with minimal effort by the engineering developers; the incorporation of a "model" (which describes precisely what an agent is capable of doing or providing and how it is accomplished) within the toolkit allows for knowledge to be generated in context allowing a designer to interrogate knowledge for the who, what, where, when, and how the information was created.
- *Computing Architecture* which includes components that are required for objects to operate in a distributed, homogeneous computing environment are included in an underlying infrastructure.

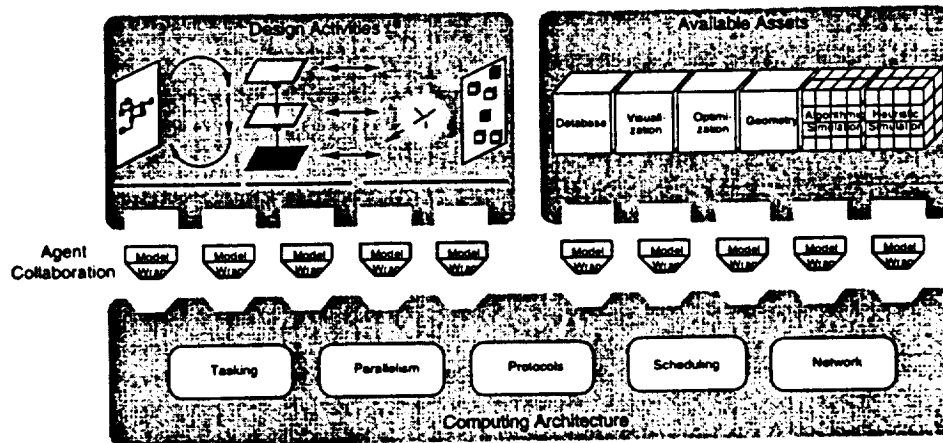


Figure 1. Infrastructure

To date approximately 60% of the basic capabilities have been developed and tested in prototype form. Year 3 plans will complete the core development and preliminary application to implementing the DREAMS methodology.

Computational Methods:

The analysis of large scale complex structures by finite element methods requires: (1) fast computational capability to satisfy the real time MDO requirement, and (2) reasonable simulation costs. To achieve the first goal, parallel matrix solution methods on a scalable massively parallel (thread-driven) machine were developed for matrix decomposition and forward/backward substitution. Two memory management schemes were considered for parallel matrix decomposition. Previous approaches used only shared memory schemes (scheme 1); a new scheme with the mixed use of local and shared memory was developed (scheme 2). Results to date show significant performance improvements in the case of a wing model using up to a 28 processor implementation. In addition, a parallel performance prediction model was designed and verified through several actual computations on a KSR computer (32 processor configuration). Estimations using this model for the wing case indicate that for scheme 1 a performance saturation will be encountered for a critical number of processors, while scheme 2 will exhibit continued performance improvement (90% performance gain over scheme 1).

In order to achieve the second goal, an optimal processor mapping algorithm for the efficient use of massively parallel processors in the concurrent heterogeneous substructure computation was developed. The algorithm uses a parallel matrix solver performance prediction model. The feasible domain is zoomed by dynamic programming, and an iterative search is performed in the zoomed zone for final solution. The results so far show good performance when applied to representative MDO tasks suitable for parallel processing.

In the area of data management, a relational database design was developed for the conceptual design phase of the HSCT in order to evaluate how data management can aid in improving the efficiency of the aircraft design process. The steps utilized in the database design synthesis included: (1) representation of the conceptual design process, (2) development of a data dictionary, and (3) determination of data relationships. IDEF0 modeling methodology was used to produce a function model of the conceptual design process. The IDEF0 model provided a structured representation of the functions of conceptual design process, and of the information and objects which interrelate those functions. The HSCT design process model developed included a database schema and a data dictionary. An IDEFIX model was used to provide a semantic data model which defined the meaning of data within the context of its interrelationships with other data. A

relational database design was initially chosen due the level of maturity of relational database technology. The intent of this initial study was to identify the processes and data requirements at the conceptual design level and to uncover those areas where further research is warranted. The relational database design synthesis provided a fundamental understanding of the basic data problems and insights into possible solutions.

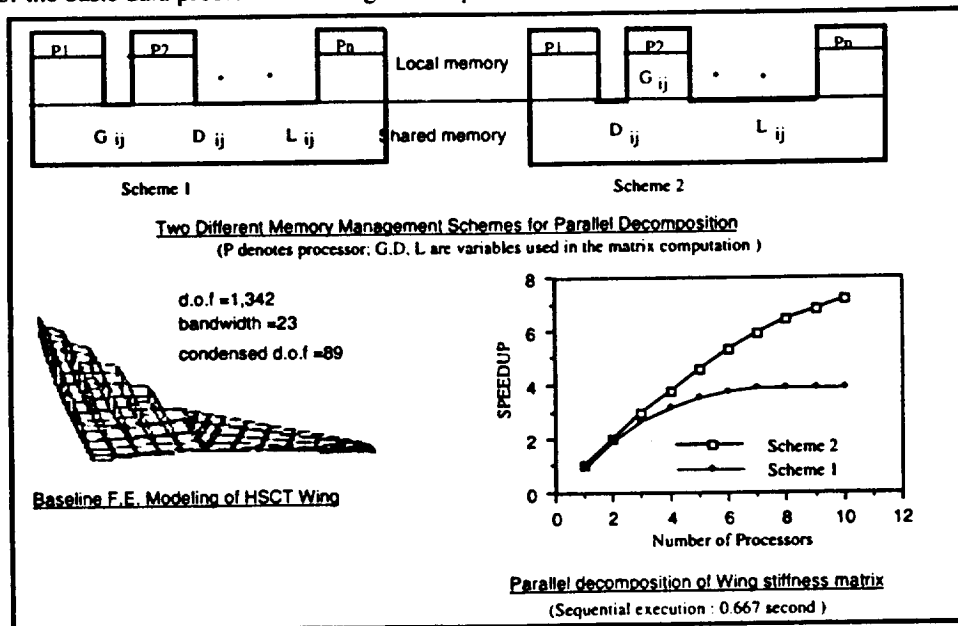


Figure 2. Problem Decomposition for Parallel Processing

Specific Applications:

A *three-level hierarchical HSCT wing design problem* has been completed and is described in a Ph.D. dissertation (Röhl 1995b). Specific analysis codes [FLOPS, ASTROS, PASCO] were integrated into a three-level framework for the structural design of the wing. The framework centers on a finite-element based structural optimization of the wing box under aerodynamic loads and subject to stress, flutter, and buckling constraints. The wing is represented by a varying complexity spar and rib model and utilizes multiple shape functions for distribution of design parameters. A wing box finite element model generator that uses system level geometric, mission and weight information to create a complete finite element design model of the wing structure and an aerodynamic panel model has been completed. An external buckling optimization procedure for buckling-critical skin panels enhances the capabilities of the structural optimization. The results of this process is depicted below in Figure 3.

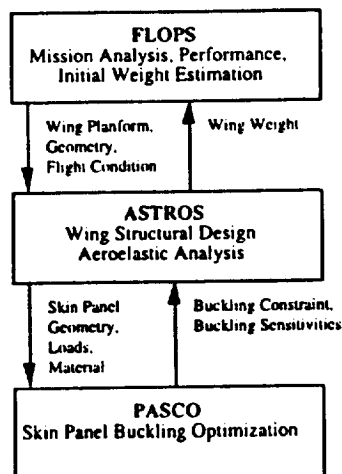


Figure 3. Multilevel Decomposition of the Wing Design Problem

Research Personnel

The key research areas identified in this Progress Report have been investigated during the past year by a number of graduate students in the ASDL, PPRL and SRL (laboratories) under the coordinated direction of the four co-principal investigators. The following table highlights the topics being investigated by the students and the footnotes indicate their current status and principal funding:

Topic	Researcher
RCEM - Robust Concept Exploration Method	Dr. Wei Chen*
IMAGE - Intelligent Multidisciplinary Aircraft Generation Environment	Mark Hale†
Information Management Strategies to Support Multidisciplinary Optimization Computations	Neil Hall
Application of Parallel Processing to Finite Element Systems	Jason Har Dr. Sang Y. Synn
The Solution of Mixed Discrete/Continuous Systems in Non-Hierarchic, Multidisciplinary Design	Kemper Lewis†
A Multilevel Decomposition Procedure for the Preliminary Wing Design of a High Speed Civil Transport Aircraft	Dr. Peter Röhl* Mr. Jae Moon Lee
Integrating Design and Manufacturing for the High Speed Civil Transport	William Marx†
Guiding Decision Based Design Processes Through Management of Design Information Content	Srinivas Vadde*

* Completed graduate studies and degree.

† NASA Graduate Student Research Program; research is closely coordinated with present program.

NEW APPROACHES TO MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

Year 2 Presentations, Publications and Workshops
Grant NGT 51102L

October 16, 1995

The following workshops and publications (referencing support from the Grant 51102L) were accomplished under the second year's research effort:

- Chen, W., Allen, J.K., Mavris, D.N., Mistree, F., Tsui, K-L, 1995b, "Integration of Response Surface Method with the Compromise Decision Support Problem in Developing a General Robust Design Procedure," *Advances in Design Automation* (Azarm, S., et al. Eds.), New York: ASME, 1995, pp. 485-492. ASME DE-Vol. 82-2.
- Chen, W., Allen, J.K., Mavris, D.N., Mistree, F., 1995c, "Robust Concept Exploration for Developing the Top-Level Specifications of Complex Systems," *Engineering Optimization*, (in press).
- Chen, W., 1995a, A Robust Concept Exploration Method for Configuring Complex Systems, Ph.D. Dissertation, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
- Hale, M. A., 1994a, "Preliminary Agent Technologies with CATIA," presented at the CATIA Operators Exchange Meeting, Dallas, October 9-13.
- Hale, M. A., 1994b, "IMAGE: A Design Integration Framework Applied to the High Speed Civil Transport," HM301: First University/Industry Symposium on High Speed Civil Transport Vehicles, North Carolina A&T State University, December 4-6.
- Hale, M.A., 1995a, "A Computing Infrastructure that Facilitates Integrated Product and Process Development from a Decision-Based Perspective," Ph.D. Thesis Proposal, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, January.
- Hale, M. A. and Craig, J. I., 1995b, "Use of Agents to Implement and Integrated Computing Environment," *Computing in Aerospace 10*, AIAA, San Antonio, TX, March 28-30, Preprint: AIAA-95-1001.
- Hale, M. A., Craig, J. I., Mistree, F., Schrage, D. P., 1995c, "Implementing an IPPD Environment from a Decision-Based Design Perspective," ICASE/LaRC Workshop on Multidisciplinary Design Optimization, Hampton, VA, March 13-16.
- Hale, M. A., Craig, J. I., Mistree, F. and Schrage, D.P., 1995d, "On the Development of a Computing Infrastructure that Facilitates IPPD from a Decision-Based Design Perspective," 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Anaheim, CA. Preprint AIAA-95-3880.
- Hall, N., and Fulton, R.E., "A Relational Database Application to Multidisciplinary Conceptual Design for HSCT," (Submitted for the publication).
- Lewis, K., Lucas, T. and Mistree, F., 1994, "A Decision-Based Approach for Developing A Ranged Top-Level Aircraft Specification: A Conceptual Exposition," AIAA/NASA/USAF/ ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, Florida, 465-481. Paper No. AIAA-94-4304-CP.
- Lewis, K. and Mistree, F., 1995a, "On Developing a Taxonomy for Multidisciplinary Design Optimization: A Decision-Based Perspective," First World Congress of Structural and Multidisciplinary Optimization, Goslar, Germany. Paper number 118.
- Lewis, K. and Mistree, F., 1995b, "Designing Top-Level Specifications: A Decision-Based Approach to a Multiobjective, Highly Constrained Problem," 36th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, New Orleans, LA. pp. 2393-2405.
- Lucas, T., 1995a, Formulation and Solution of Hierarchical Decision Support Problems, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
- Lucas, T., Vadde, S., Chen, W., Allen, J.K. and Mistree, F., "Utilization of Fuzzy Compromise DSPs for Hierarchical Design Problems", 1994, AIAA/ASME/ASCE/AHS/ACS 35th Structures, Structural Dynamics and Materials Conference, Hilton Head, South Carolina, pp. 1753-1763. Paper No. AIAA-94-1543-CP.
- Mistree, F., Lewis, K. and Stonis, L., 1994, "Selection in the Conceptual design of Aircraft," AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, Florida, 1153-1166. Paper No. AIAA-94-4382-CP.
- Röhl, P.J., Mavris, D.N., and Schrage, D.P., 1994, "A Multilevel Decomposition Procedure for the Preliminary Wing Design of High-Speed Civil Transport Aircraft," First Industry/Academy Symposium on Research for Future Supersonic and Hypersonic Vehicles, Greensboro, NC, December.
- Röhl, P.J., Schrage, D.P. and Mavris, D.N., 1995a, "Combined Aerodynamic and Structural Optimization of a High-Speed Civil Transport Wing," 36th AIAA Structures, Dynamics, and Materials Conference, New Orleans, LA, April, Preprint AIAA 95-1222.

- Röhl, P.J., 1995b "A Multilevel Decomposition Procedure for the Preliminary Wing Design of a High Speed Civil Transport Aircraft," Ph.D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, June 1995.
- Röhl, P.J., Mavris, D.N., and Schrage, D.P., 1995b, "Preliminary HSCT Wing Design Through Multilevel Decomposition," 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Los Angeles, CA, September 19-21, AIAA 95-3944.
- Simpson, T.W., 1995a, Development of a Design Process for Realizing Open engineering Systems, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, August 1995.
- Simpson, T.W., Bauer, M.D., Allen, J.K. and Mistree, F., 1995b, "Implementation of DFA in Conceptual and Embodiment Design using Decision Support Problems," *ASME Advances in Design Automation* (Azarm, S., et al. Eds.), New York: ASME, pp. 485-492. ASME DE-Vol. 82-2.
- Synn, S.Y. and Fulton, R.E., 1994a, "The Concurrent Element Level Processing for Nonlinear Dynamic Analysis on a Massively Parallel Computer", Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, (also in *Journal of Computer Systems in Engineering*).
- Synn, S.Y. and Fulton, R.E., 1994b, "The Prediction of Parallel Skyline Solver and its Implementation for Large Scale Structural Analysis," Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, (Also, in *Journal of Computer Systems in Engineering*).
- Synn, S.Y., 1995a, "Practical Domain Decomposition Approaches for Parallel Finite Element Analysis," Ph.D. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, January 1995.
- Synn, S.Y. and Fulton, R.E., 1995b, "Practical Strategy for Soncurrent Substructure Analysis," *Journal of Computers & Structures*, Vol.54, No.5.
- Synn, S.Y., Schwan, K., and Fulton, R.E., 1995c, "Analysis of Large Scale Heterogeneous Structures on Massively Parallel Computers," *Journal of Concurrency: Practice and Exercise* (Submitted for the publication in the *Journal of Concurrency, Practice/Experience*).
- Vadde, S., 1995, *Modeling Multiple Objectives and Multilevel Decisions in Concurrent Design of Engineering Systems*, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
- Vadde, S., Allen, J.K., Lucas, T. and Mistree, F., 1994, "On Modeling Design Evolution along a Design Time-Line," AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, Florida, 1474-1482. Paper No. AIAA-94-4313-CP.

Workshops Supported by NASA Grant NGT 51102L:

HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1995.

APPENDIX D. YEAR 3 REPORT

NEW APPROACHES TO HSCT MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

Year 3 Interim Progress Report NGT 51102L

January 1996

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PROJECT OVERVIEW

The successful development of a capable and economically viable high speed civil transport (HSCT) is perhaps one of the most challenging tasks in aeronautics for the next two decades. At its heart it is fundamentally the design of a complex engineered system that has significant societal, environmental and political impacts. As such it presents a formidable challenge to all areas of aeronautics, and it is therefore a particularly appropriate subject for research in multidisciplinary design and optimization (MDO). In fact, it is starkly clear that without the availability of powerful and versatile multidisciplinary design, analysis and optimization methods, the design, construction and operation of an HSCT simply cannot be achieved. The present research project is focused on the development and evaluation of MDO methods that, while broader and more general in scope, are particularly appropriate to the HSCT design problem. The research aims to not only develop the basic methods but also to apply them to relevant examples from the NASA HSCT R&D effort. As shown in Figure 1 below the research involves a three year effort aimed first at the HSCT MDO problem description, next the development of the problem, and finally a solution to a significant portion of the problem.

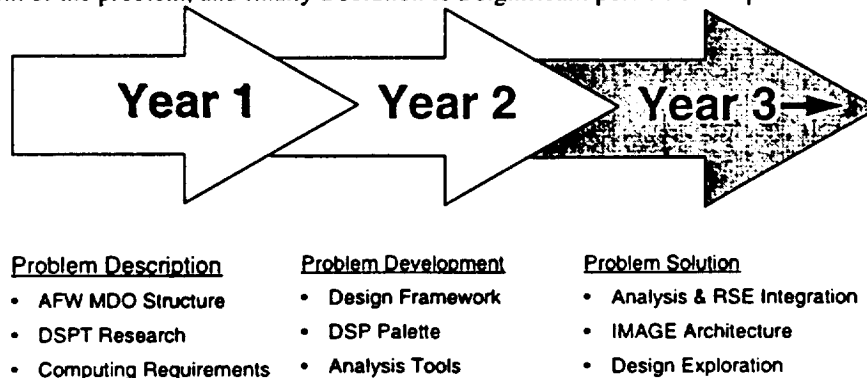


Figure 1. Three Year Task Schedule

The Year 1 effort focused on identification of a specific (and academically "tractable") portion of the broader HSCT design problem. The initial attention was on the HSCT wing design including both the product and process development aspects, but the focus has shifted towards the multidisciplinary effort to handle the aeroelastic design of the wing and more specifically the case of an "active aeroelastic wing" (referred to as AAW or AFW for "active flexible wing"). Year 1 effort was also spent on adaptation and development of basic decision support methods to the problem and on the development of computing requirements for a practical system. The Year 2 effort involved the further development of the wing design framework, the development of specific classes of decision support problems (DSP palettes), and the identification and development of specific analysis tools. The present Year 3 effort involves incorporation of robust design simulation methods involving the use of response surface equations (RSE's) to bring high-fidelity, discipline-specific analysis and modelling methods forward into conceptual design studies from their more traditional places in subsystem level preliminary design efforts. These methods and tools are now being tested and evaluated in sample MDO studies using the IMAGE design computing architecture.

YEAR 3 OBJECTIVES AND RESULTS

Research under the subject grant is being carried out in a jointly coordinated effort within three laboratories in the School of Aerospace Engineering and the George Woodruff School of Mechanical Engineering (see Figure 2 and titles above). The objectives and results for Year 3 (interim) of the research program are summarized the table below. The "Objectives" and "Expected Significance" are taken directly from the Year 3 Proposal presented in October 1995, and "Results" summarize what has been accomplished for the funded portion of this past year. A discussion of these results is provided in the following sections. A listing of papers, presentations and reports that acknowledge grant support, either in part or in whole, and that were prepared during the entire contract period is provided in an attachment.

Objectives	Expected Significance	Results
1. Complete Development of IDES, including the identified high performance computing environment.	1. Provides significant improvement in the support provided to designers of advanced aerospace vehicles.	1. A step by step approach based on the response surface method, decision support techniques, and a computing infrastructure (IMAGE) has resulted in the described simulation environment.
2. Demonstrate the IDES addressing the design of a HSCT wing using advanced technologies and their impact on the overall economic viability	2. Provides demonstration of IDES capabilities and a test case for other IDES users.	2. Initial demonstration problem completed and documented: HSCT system level synthesis with cost as the key objective and wing aerodynamic and structural technologies modeled.
3. Identify additional New Approaches for incorporation into IDES. Include an integrated aero-structures-control HSCT wing demonstration in IDES and address the tradeoffs between product and process enhancements.	3. Provides for continuous improvement to IDES through its open architecture.	3. Continuous improvement translates to new technologies: initial methodology to design for Active Aeroelastic Wing Technology developed, encompassing multidisciplinary interactions (aero-structure-controls).

1. DEMONSTRATION OF NEW APPROACHES: INTEGRATING THE RESEARCH

Research in Years 1 and 2 focused on specific method development for MDO applications. Three key results include the following. Implementation of the multilevel wing optimization strategy developed in the first year effort resulted in a tool for multidisciplinary wing design, documented in Dr. Röhl's Ph.D. Thesis [Rohl (95)], which was used for optimal wing jig shape and aeroelastic tailoring studies in consideration of buckling constraints. A *robust concept exploration method* has been developed by Dr. Chen and documented in her Ph.D. dissertation [Chen (95)]. Finally, a unique computing infrastructure for design has taken shape through the work of Dr. Hale [Hale (96c)]. However, the final objective of Georgia Tech's efforts towards "New Approaches to MDO" was not the production of useful, but disparate, tools. Instead, the driving motivation is *system synthesis* through the intelligent integration of these MDO tools. Year 3 results described below highlight this emphasis. Such synthesis is especially important for the evaluation of new technologies, such as the Active Aeroelastic Wing concept under development by Rockwell International, a partner with Georgia Tech for the past three years.

Integration of the tools and techniques developed was guided by NASA Langley's MDO research and Technology Program Strategic Plan for MDO, which identified the three generic elements of MDO: data management, design-oriented analysis, and design space search. We have cast the elements in the setting of *system synthesis*, since this is ultimately where important objectives (especially cost) are realized. Consistent with our previous research under this grant, the HSCT provides the specific testbed for demonstrating the integration of the three MDO elements for the purpose of making intelligent design decisions, using the proper objectives at each point in the design timeline. The aeroelastic analysis and design of the HSCT wing is the subsystem which provides the impetus for developing better design oriented analysis. The result of these Year 3 integration activities are described next.

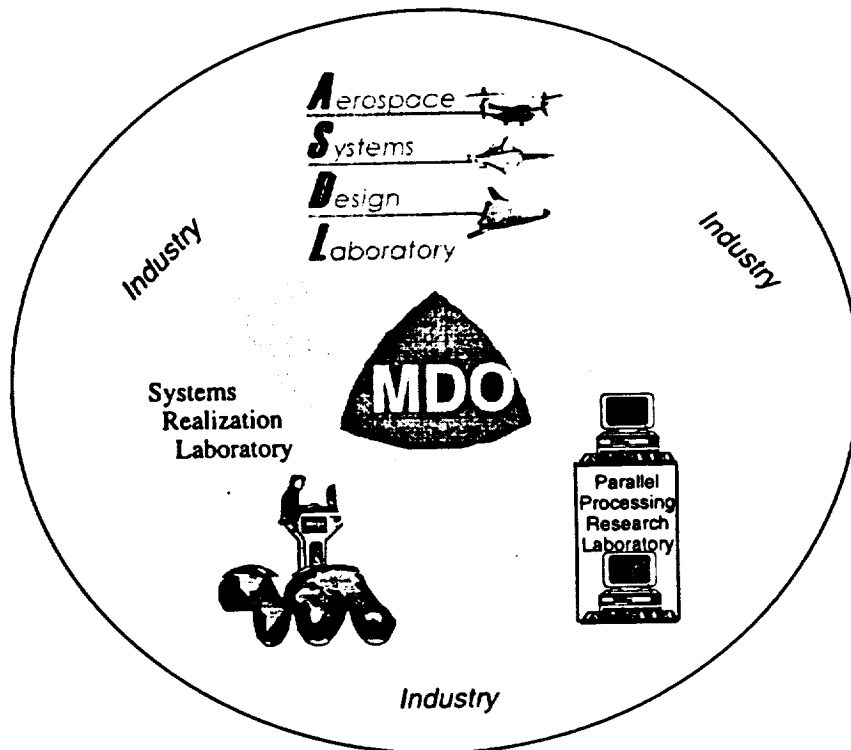


Figure 2. Coordinated University/Government/Industry Team

2. DEMONSTRATION OF NEW APPROACHES: SYSTEM SYNTHESIS OF THE HSCT, WITH AN AERO-STRUCTURE-CONTROL APPLICATION

One portion of the research under New Approaches attempts to tackle the design-oriented analysis dilemma by *combining* the empirical and idealized analysis approaches in order to provide the desired relationship between design variables and the key aircraft quantities required for synthesis. To do so, two complimentary statistical techniques, the Design of Experiments (DOE) and Response Surface Methodology (RSM), are used for the purpose of forming expressions for the relationships based on complex analyses. These expressions are called Response Surface Equations (RSEs). DeLaurentis [96a] describes the use of statistical techniques for aerodynamic *modeling* and system *optimization*. Mavris [96a] presents the use of RSEs in the realm of aircraft economic viability assessments.

Even with the availability of improved disciplinary information, designers are still faced with how to best manage and make decisions upon this information. The lack of a solid formulation for a design space search and the inability to conduct searches by tailoring the computing design process are deficiencies which contribute to decision making difficulties. In more general terms, there has been a lack of viable distribution schemes for implementing large-scale problems within computing frameworks. A design-oriented computing infrastructure addresses these problems through a joint process and information modeling scheme that supports evolutionary design activities. One such infrastructure has been created and is used in the current research effort. This scheme is suited for small design tasks as well as large, proprietary, distributed analysis efforts. This computing infrastructure is based on a well defined and tested system for seeking solutions: the Decision Support Problem Technique described in [Mistree (93)]. The application problem discussed below will demonstrate how a design problem can be managed and areas of good solutions can be found based on potentially conflicting goals and constraints.

What is to follow will describe a synthesis simulation environment which is well suited for the introduction, modeling, and evaluation of *innovative* technologies. These technologies motivate the need to search for ways to include complex, interdisciplinary analysis in system level optimization and for improved design decision making through an understanding of the relationship between fundamental design variables and system objectives. The status of method development at this point in the Year 3 effort is discussed first followed by a highly detailed example problem involving the disciplines of aerodynamics, structures, and controls. The example completed through a search for good wing planform designs for an HSCT considering static and dynamic aeroelastic constraints as well as system level performance constraints.

Design Oriented Analysis Via Approximation Functions

As more and more problems that were traditionally solved in isolation are approached from a multidisciplinary point of view, design-oriented analysis has become increasingly important. One such problem is the aeroelastic design of supersonic transport wings with system level objectives. Numerous techniques have been developed and demonstrated which focus on the wing design aspect. It is the efficient integration and use of this "sub-problem" in a system synthesis environment that has not received significant attention. Under New Approaches research, analysis techniques usually associated with design stages where key geometric variables have been fixed, such as the use of Finite Element Models (FEM), are utilized in a design space consisting of these important geometric parameters. This is accomplished through the combined use of DOE/RSM and parametric analysis tools. *It soon becomes apparent that the most critical parametric tool required is an automated FE grid generator* [Rohl (95)]. Once the capability to rapidly model and analyze different wing planforms is obtained, an approximation function for the structural weight of an aeroelastically optimized wing can be constructed. Thus, the specific problem of integrating system and discipline level design environments is addressed, and cost, performance, and manufacturing trades can be made (representing the primary thrust of the so called Integrated Product and Process Development (IPPD) philosophy).

Often the relationship between some quantity of interest (a response) and predictors (input variables) is either too complex to determine or unknown. In these cases, an empirical approach is necessary to determine the behavior and this provides the basis for the Response Surface Methodology (RSM). RSM is comprised of a group of statistical techniques for empirical model building and exploitation. By careful design and analysis of experiments, it seeks to relate a response, or output variable, to the levels of a number of predictors. The Design of Experiments, as the name suggests, originates from the experimental fields where empirical relations were sought due to the unavailability of analytical models. In the application of the current research, the "experiments" are actually "simulations", but the goal is the same: construct an empirical model where an analytical model is unavailable or impractical. Clearly, this model building approach can assist in the formation of design-oriented analysis.

The implementation of RSM results in Response Surface Equations. RSEs are regression equations which seek to represent analysis of a phenomenon in the form of equation(s) consisting of the factors (or design variables) which are known to be functionally related to the phenomena. Since synthesis codes rely on increasingly outdated databases and more sophisticated disciplinary codes often are too cumbersome to be embedded in a design optimization loop, RSEs bridge the gap between what is needed and what is available. Further, DOE/RSM is just one of several methods available for function approximation and model building. Fuzzy Logic and Neural Networks are two recent, promising techniques in this area.

DOE provides an organized way of obtaining data for the regression analysis and a technique for avoiding the "curse of dimensionality". The DOE is used to determine a table of input variables and combinations of their levels which can be analyzed to yield a response value. This also encompasses other procedures such as Analysis of Variance. Full-factorial designs are used to construct model equations which account for all possible combinations of variable settings. Fractional factorial DOEs are used to produce results similar to full factorial designs, but require less information and consequently fewer analyses. This is accomplished by reducing the scope of the model to only account for effects of interest.

A generalized RSE is shown in EQ (1) where main, quadratic, and second order interactions effects are shown.

$$R = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{i < j}^k b_{ij} x_i x_j \quad (1)$$

where,

b_i are regression coefficients for the first degree terms,

b_{ii} are coefficients for the pure quadratic terms,

b_{ij} are the coefficients for the cross-product terms

A trade-off exists when exercising fractional factorial designs. The number of simulations (experiments) required grows as the increasing degree to which interaction and/or high order effects are desired to be estimated. Since generally only a fraction of the full factorial number of cases can realistically be executed, estimates of high order effects and interactions are often not possible. They are said to be confounded, or indistinguishable, from each other in terms of their effect on the response. This aspect of fractional factorial designs is described by their *resolution*. Resolution III implies that main effects are entirely confounded with second order interactions. Thus, one must assume these interactions to be zero or negligible in order to estimate the main effects. Resolution IV indicates that all main effects can be estimated, though second order interactions are confounded with other such interactions. Resolution V means that both main effects and second order interactions can be estimated. However, for Resolution V designs, third order interactions would be confounded with second order effects, and hence they would not be distinguishable [DeLaurentis (96a)]. In our HSCT

wing structural weight example presented, a second degree polynomial model of the selected responses in k-variables is assumed to exist as in eq. (1).

Design Decision Making in Wing Design

The aeroelastic wing design method used in conjunction with the DOE/RSM is described in detail in DeLaurentis [96b]. The framework centers on a finite-element based structural optimization of a wing box under aerodynamic loads that is subject to stress and flutter constraints. The wing is represented by a varying complexity spar and rib model and utilizes multiple shape functions for distribution of design parameters. A initial wing box finite element model generator that uses system level geometric, mission, and weight information to create a complete mesh of the wing structure has been completed [Rohl (95)]. A maneuver load program, called Integrated Structure/Maneuver Design (ISMD), provides for the computation of static external loads [ISMD-Rockwell (95)]. The key objective of the wing design procedure here is a balance between the desire for a parametric procedure and a desire for increased analysis accuracy. A method for achieving this balance will be demonstrated in the simulation experiment below.

The MDO methodologies developed in the present work are coordinated in an MDO *infrastructure and integration* project which has become to be known as DREAMS (Developing Robust Engineering Analysis Models and Specifications) [Hale (96a)]. This work resulted in the development of an *open* computing infrastructure that facilitates the design of complex engineering systems. This infrastructure is called IMAGE (Intelligent Multidisciplinary Aircraft Generation Environment). IMAGE is considered open for two reasons [Hale (96b)]. First, the infrastructure permits *freedom* for a designer to model both processes and information as required at a particular point in a design's timeline. This is accomplished through an information model which incorporates schema evolution. Schema evolution is a general term used to describe an information model that captures time-dependent product and process characteristics at varying degrees of accuracy and fidelity. As a result, product descriptions can be modified as fidelity increases. In the case of a wing design, an initial product description is based on parametric components. During finite element analysis, a more detailed model is required that includes node and member definitions. Both of these representations can coexist-exist in the information model. Moreover, specific instances (e.g. values) can be accumulated for decision-making and optimization.

IMAGE facilitates a necessary paradigm shift in early conceptual solution algorithms. Ultimately design processes culminate in decision-making. These are represented by discrete milestones in a design's life-cycle. At each milestone, a designer desires to know as much about a problem before further restricting a design. Before eliminating alternatives or reducing product families, potential technologies or applications should be explored. This can be accomplished by applying various solution techniques. An example that illustrates the benefits of applying alternate solution strategies follows.

Traditionally, decisions have been based on optimality criteria imposed locally on a limited design representation. As designs progress, either local or system level changes may cause an optimal target to shift, rendering the design infeasible. The ideas behind optimal solutions are depicted in Figure 3. Initially, a system may optimally satisfy problem constraints and customer requirements, represented by peaks in the solution space shown in Figure 3. A particular problem solution is represented by a ball in the figure. A problem shift will cause the system to deviate from an optimal solution, thus rendering the initial solution to be sub-optimal or even infeasible.

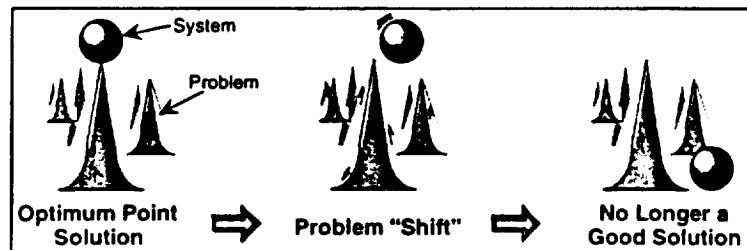


Figure 3. An Optimal Solution

To utilize alternative solution techniques, a paradigm shift must occur whereby design freedom is left open in earlier design stages. This can be accomplished through the use of a satisficing solution. A satisficing solution is one that provides a region of solutions that minimizes the deviation between customer and manufacturer requirements and design constraints, bounds, and goals. The template used to describe this type of formulation is referred to as a Compromise Decision Support Problem. [Mistree (9x); Bras (91)] As a result, a designer can base decisions about a design on regions of plausible design derivatives/alternatives that exist at that point in design time. A pictorial aid for the notion of

satisficing solutions is presented in Figure 4. Optimal peaks are replaced by satisficing mesas, leading to robust design solution regions. Early in the design process, a designer bases decisions on a region of acceptable design solutions. As the region evolves throughout design processes, particular design decisions remain valid and lie within the region of candidate solutions (a mesa).

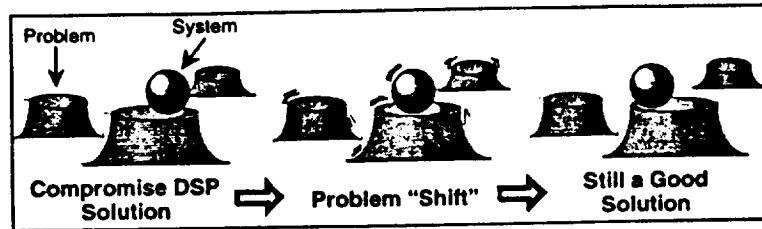


Figure 4. Satisficing Solution Used Early in Design

The methods employed during the determination of satisficing solutions lend themselves to the more recent use of approximation techniques. Using these techniques, continuous representations of particular analyses are created (to a known degree of accuracy) and are used in place of the original analysis tools. Using these approximations permits rapid concept exploration during conceptual design as well as the incorporation of probabilistic methods [DeLaurentis (96a)]. In addition, a designer has the capability to make design decisions based on downstream information brought into earlier design stages.

These two models, satisficing and optimal, are encountered as Support Problems are used in design processes. As shown in Figure 5, satisficing solutions are used early in design processes since less is known about designs. Represented by a fading timeline, the need and use of satisficing solutions diminishes as a design progresses. As designs are refined, more is known about a design and a designer begins to look for solutions that approach optimal type solutions, as seen in Figure 6. At this point, traditional optimization methods as well as newer global sensitivity approaches may be used to aid in problem solution.



Figure 5. Satisficing Solution Used Early in Design



Figure 6. Optimal Solution Used Later in Design

Simulation Exercise: Synthesis with Aeroelastic Wing Design

The complex problem of finding good designs for a flexible HSCT wing based on the combined (and generally conflicting) objectives of minimum cost and maximum performance will be exercised in this demonstration of the developed simulation environment. The solution of this problem requires the combined analysis capabilities from the aerodynamics, structures, and controls disciplines. In addition, the simulation is multi-leveled, with objectives calculated at the system level through sizing and synthesis but with most of the design parameters distributed in subsystem level disciplines. The contributing analyses introduced through response equations allow a designer to perform tradeoffs in terms of the size of the design space searched and complexity of the tools used. A hierarchical system decomposition summarizing the problem is illustrated in Figure 7.

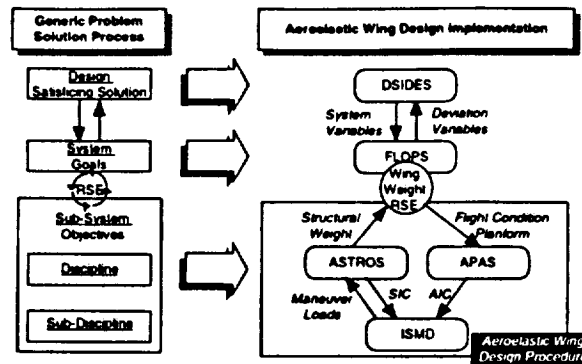


Figure 7. Hierarchical System Decomposition

Wing Design Level

The objective at this level is to use FEM-based analysis to construct an RSE which relates geometric wing design parameters to wing structural weight. A detailed description and exposition of the FEM model used and the analysis procedure is contained in DeLaurentis (96b). With the aid of Figure 8 and the paragraphs below this procedure is described. First, a DOE is selected to define a series of wing planforms which form the design space. These planforms become inputs to the aerodynamic-structures-loads analysis shown in Figure 8. The mesh generation procedure developed translates the aerodynamic grid (to which the air and inertia loads are applied) into an "equivalent" structural grid (FEM nodal mesh). The structural grid is used by the Automated STRuctural Optimization System (ASTROS), developed at Wright Laboratory, for weight distribution among the modeled spars, ribs, and spar caps to satisfy strength and flutter constraints given the applied net loads (air and inertia loads combined) due to maneuver. The structural and aerodynamic interactions are represented through structural influence coefficients (SICs) and aerodynamic influence coefficients (AICs). AICs relate aerodynamic loads to changes in local panel angles of attack while SICs relate normal deflections of the panels with application of a unit load.

The ISMD code uses the SICs (from ASTROS) and AICs to calculate trim control surface settings and the resulting net loads on the model. These net loads must later be transformed into the structural grid. For this study, an expected worst case static loading condition is assumed to be a 2.5-g symmetric pull-up at a Mach number of .9 and altitude of 30,000 ft. This maneuver is used to generate the trimmed static loads in ISMD. The output of the ASTROS/ISMD iteration is the converged wing structural weight for that particular planform and loading condition (see Figure 8). This procedure is based on the method outlined in Miller (94).

In the ASTROS optimization, mass is redistributed in an attempt to reduce structural weight while satisfying strength and flutter constraints. The flutter condition of Mach 3.12 at an altitude of 60,000 ft. is also investigated in the optimization for each case. An assumption inherent to the use of an RSE approach is that since flutter is met for all data points in the DOE, then flutter will be met for all points within design space. At minimum, this assumption should be checked on any configurations which result from the design space search. Structural optimization information (e.g. converged element thickness' for each case of the DOE) is not carried through to the RSE but can be retained separately if desired.

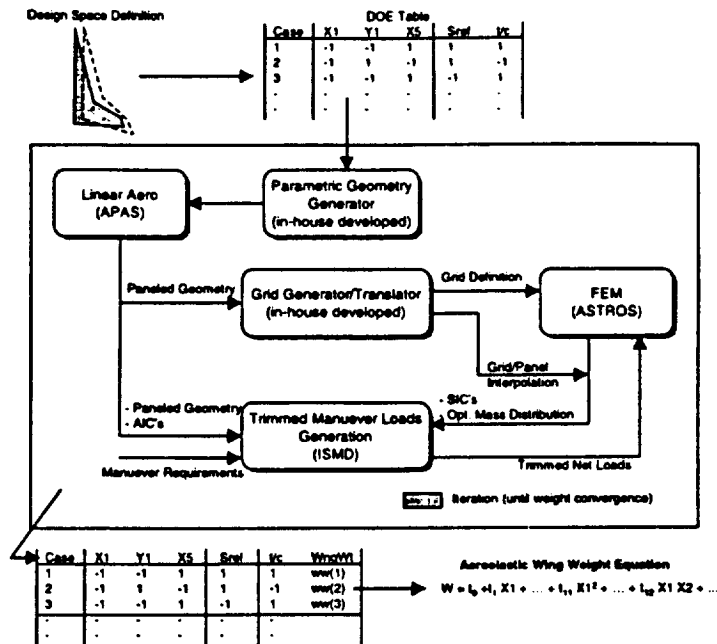


Figure 8. Aeroelastic Wing Design Procedure [DeLaurentis(96b)]

A five-variable, face-centered design tested at three levels is chosen for the DOE. It is a Resolution V design, meaning both main effects and second order interactions are accounted for and are not confounded with each other. This results in 27 distinct simulations which need to be performed. The variables and their selected ranges for the DOE are shown in Table 1. These variables correspond to the definitions shown in Figure 3, and the variables $X1$, $Y1$, and $X5$ are normalized by the wing semispan and defined from an origin at the wing root leading edge. Additional variables are defined in Figure 9, some of which will be used in the system design problem.

Table 1. Design Variables and Ranges

Description	Variable Name	Minimum Value	Maximum Value
Kink X-location	X1	1.54	1.69
Kink Y-location	Y1	0.44	0.58
Root Chord	X5	2.19	2.36
Wing Reference Area (ft ²)	Sref	8500	9500
In-Outboard Thickness (%)	t/c	2.5	3.3

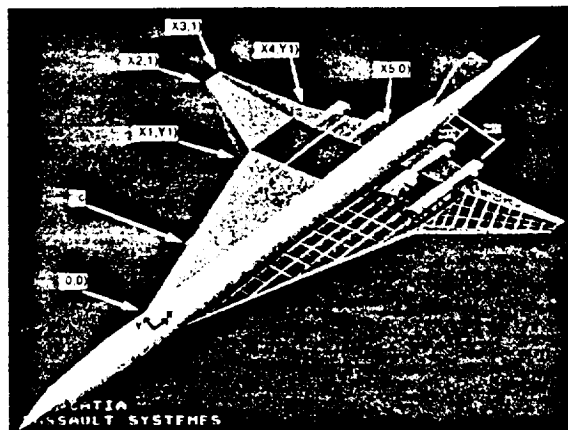


Figure 9. Design Variable Definitions

It seems clear that five wing design variables and one flutter condition may not be detailed enough for a design problem in an industrial setting. We agree. However, a fundamental goal of this Year 3 effort is to establish a "Proof of Concept" and demonstrate the feasibility of the concept on a manageable complexity level. If the demonstration is successful, more detailed contributing analyses (e.g. doubling the number of FEM nodes, adding flutter cases, etc.) should only add time to the RSE construction process, not necessarily difficulty. A key fact to remember is that even a DOE/RSM scheme can be impractical if the number of design parameters and/or the analysis execution times are unreasonably high.

Returning to the problem at hand, each of the different cases (i.e. planform shapes) from the DOE is executed according to the procedure in Figure 8. At this point in this study, only one ASTROS/ISMD iteration is performed since it was felt that the coarseness of the structural model did not warrant any further convergence tolerance. The resulting responses are collected and an RSE for wing weight as a function of planform variables is formed. This RSE is then used to replace the estimate used in the synthesis code FLOPS (FLight OPTimization System, NASA Langley), whose wing weight prediction is based on historical data of mostly dissimilar wing shapes.

The second order polynomial wing weight RSE based on the variables in Table I is depicted in Figure 10(a) in the form of a prediction profile with the design variables at their midpoint settings. The "-1" and "1" limits represent the normalized minimum and maximum settings given in Table I. The center value on the ordinate is the half-model, structural wing weight based on the current settings of the five design variables. A first check of the validity of the equation involves examining the trends. For example, increasing $X1$ and decreasing $Y1$ together lead to an outboard shift of the wing area distribution (see Figure 9 and Figure 10 (b)). Thus, an increase in weight is expected and indeed is borne out in the profile for those variables in Figure 10 (b). An important attribute of the DOE/RSM approach used here is that *a direct, quantifiable link between weight prediction and fundamental design variables of interests (and their interactions) is obtained*. This can be invaluable in conducting sensitivity analysis and/or finding feasible regions of good designs.

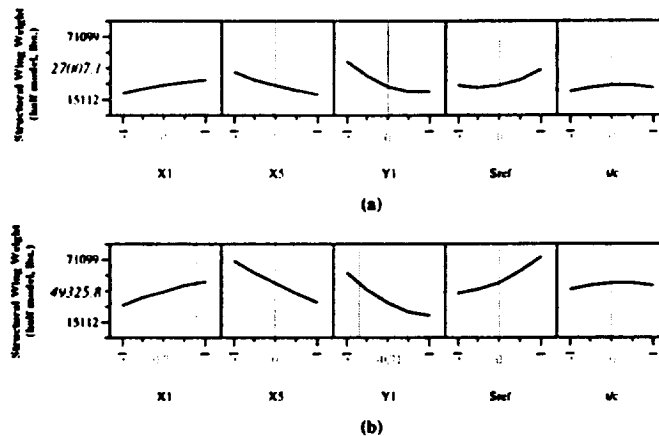


Figure 10. RSE for FEM Supersonic Transport Wing Weight Equation: (a) Prediction Profile for Midpoint Settings; (b) Example of Increasing Weight as Kink Locations Moves Inboard

A series of measures can be investigated which pertain to the quality of the regression. The most common is the R-Square value. The R-square value is the square of the correlation between the actual and predicted responses. Thus, an R-square value of one implies that all the fit errors are zero (i.e. a perfect fit). The R-Square value for the RSE in Figure 10 is .9900, a satisfactory result.

System Synthesis Level

With the structural wing weight RSE in hand, attention turns toward its role in the sizing and synthesis code FLOPS. Aircraft sizing algorithms, including FLOPS', center around a fuel balance. A vehicle is "defined" by the specification of drag polars at multiple flight conditions as well as engine performance in the form of thrust and fuel flow tables. This vehicle is then "flown" along a designated mission through climb, cruise, descent, etc. If, at the end of the mission, the fuel available (determined from volume considerations) is equal within some tolerance to the fuel required (fuel used to fly the mission plus reserve fuel), the aircraft is said to be sized. If not, an iteration takes place by increasing/decreasing the fuel available as appropriate and re-flying the mission. Once converged, the main outputs include gross weight, fuel weight, and values for any number of performance constraints.

Multidisciplinary analysis takes place in the sizing code through the interaction of the disciplinary RSEs. Aerodynamic RSEs for a supersonic transport were generated and incorporated into FLOPS [DeLaurentis (96a)]. In that application, the response was the components of vehicle drag as a function of geometry (see Figure 3) and flight condition for a supersonic transport. In a similar manner, for the problem studied in this presently, the wing structural weight RSE generated is integrated into FLOPS to replace the existing prediction method. These equations are presently used concurrently during the sizing and synthesis process and are based on the same set of design variables and ranges.

Ultimately, however, the key attribute of the supersonic transport wing weight RSE, when embedded in the synthesis code, is that it provides a formulation that shows the correct trends as a function of geometric characteristics and based on sophisticated analysis

Design Level

Once the RSE's have been implemented in the new FLOPS tool, the system synthesis procedure is modeled in IMAGE. The aeroelastic wing design problem is cast as a Compromise Decision Support Problem. Here a satisficing solution is sought that minimizes the deviation among takeoff gross weight, fuel weight, and required yield per revenue passenger mile from their respective goals. A satisficing solution is particularly important at this point in the design cycle because the location of a *region of particularly good designs* is desired. The objective is to find a robust design and not a single design candidate.

The Compromise DSP Template is shown in Figure 11. This Template is entered into IMAGE using a Graphical User Interface (GUI). During the solution of this Compromise DSP, the FLOPS tool containing the wing weight RSE will be executed in order to determine the design variable states for constraint, goal, and deviation function calculations. The template depicts the *conflicting* system goals: minimize takeoff gross weight (TOGW), ticket price (required average yield per revenue passenger mile, \$/RPM), and takeoff flyover noise. Constraints are both explicit (Takeoff Field Length, TOFL, Landing Field Length, LFL, and Approach Speed, Vapp) and implicit (flutter, strength, etc.). Using IMAGE, FLOPS can be linked directly to the System Support Problem defining the Palette for the Compromise DSP. If FLOPS were separated into its disciplinary modules, each module could be linked to functionally independent System Support Problems. Thus, the modular aspects of using IMAGE are easy to utilize.

System design variables for this exercise include a set of parameters normalized by the wing semispan which uniquely define a cranked planform, such as the one envisioned for an HSCT. These are defined in Figure 9. Note that several of these variables are common to the wing weight RSE. As DSIDES varies the system level variables, the wing weight is recalculated during aircraft sizing in FLOPS via the response equation. RSEs based on these same planform variables which predict vehicle aerodynamics were formed [DeLaurentis (96a)] and are also embedded in FLOPS in this exercise.

Given:

- FLOPS v5.7
- Response surface equations for Aero/Structures/Control Module in FLOPS
- # passengers NPT = 300
- Mission profile (altitude, range, reserve fuel, etc.)
- Generic HSCT baseline configuration
- Overall design requirements including constraints, C(X), and goals, G(X)

Find:

- The system variables, X
 - Leading edge kink, X1
 - Leading edge tip, X2
 - Trailing edge tip, X3
 - Trailing edge kink, X4
 - Root chord, X5
 - Kink locations, Y1
 - Position of wing on fuselage, XWING
 - Thrust-weight ratio, TW
 - Wing area, SREF
- The values of the deviation variables associated with goals, G(X):
 - Takeoff gross weight, TOGW(X): d1-, d1+
 - Flyover noise, FNOISE(X): d2-, d2+
 - S/RPM, DRPM(X): d3-, d3+

Satisfy:

- The system constraints, C(X), as determined by FLOPS
 - takeoff field length \leq upper bound
TOFL(X) \leq 11,000 ft
 - landing field length \leq upper bound
LFL(X) \leq 11,000 ft
 - approach velocity \leq upper bound
VAPP(X) \leq 155 kts
 - lower bound \leq second segment climb gradient
SCLBG(X) \geq 0
 - lower bound \leq missed approach climb gradient
ACLBG(X) \geq 0
- The system goals, G(X), as determined by FLOPS
 - Minimize takeoff gross weight, TOGW(X):
$$\text{TOGW}(X)/825,000 + d1^- - d1^+ = 1.0$$
 - Minimize flyover noise, FNOISE(X):
$$\text{FNOISE}(X)/104.0 + d2^- - d2^+ = 1.0$$
 - Minimize S/RPM, DRPM(X):
$$\text{DRPM}(X)/0.11 + d3^- - d3^+ = 1.0$$
- The bounds on the system variables

Minimize:

- A deviation function associated with:
 - Takeoff gross weight, TOGW(X), d1+
 - Flyover noise, FNOISE(X), d2+
 - S/RPM, DRPM(X), d3+
- $$Z = \{f1(d1+), f2(d2+), f3(d3+)\}$$

Figure 11. Compromise DSP Template for Wing Design

Given the DSP and associated assumptions, the DSIDES code is used to find the values of the system design variables which minimize the deviations of the goals from their respective targets while satisfying the imposed constraints.

Simulation Results

The Aeroelastic Wing Design Problem is solved using IMAGE, the modular architecture for design decision-making. Recall that the wing weight RSE has been integrated into FLOPS. In turn, FLOPS is made into an agent for integration into the overall architecture. IMAGE will utilize FLOPS as a tool which is used to determine responses to the system variables (e.g. namelist variables are changed the new aircraft is sized).

IMAGE calls DSIDES as the toolkit used to solve the Compromise Decision Support Problem that is shown in Figure 11. DSIDES uses an Adaptive Linear Programming (ALP) algorithm to determine the perturbations in system variables. These perturbed variables are input into FLOPS and then FLOPS is executed to determine the values of the variables

associated with the goals. The nonlinear goals and constraints are calculated by IMAGE and given back to DSIDES so that the solution process can continue.

A screenshot of this problem implemented in IMAGE is shown in Figure 12. This shows the Palette Network used to define the problem. This particular network is not complex because the problem solution only requires the execution of FLOPS. FLOPS is executed on an RS6000/320H and IMAGE is running on a Sparc 1000. An object editor is shown where problem variables, goals, constraints, etc. are entered into the database by a designer. Finally, an interface is shown that depicts the system variable history as DSIDES determines a satisficing solution.

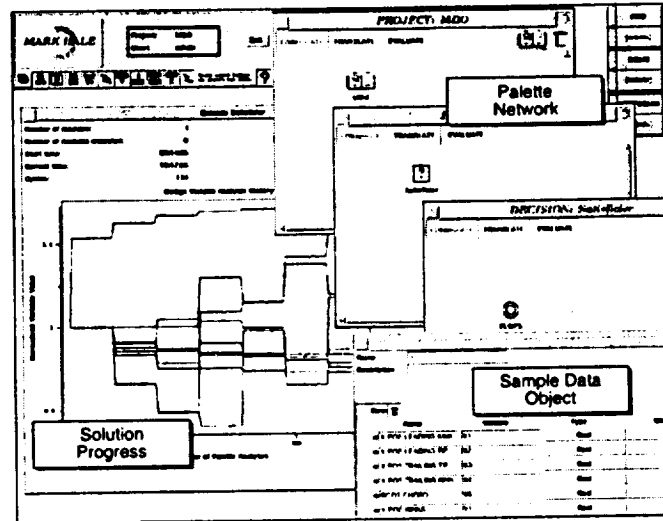


Figure 12. Screenshot of IMAGE During Execution

The Compromise DSP from Figure 11 is entered into IMAGE via a Graphical User Interface. For this analysis, the deviation function chosen is an Archimedean which can be compared to traditional synthesis studies. A Preemptive Formulation is currently being studied and will be discussed later. In the Archimedean Function, deviation variables are weighted relative to each other. Goals are set for each of the deviation variables representing Takeoff Gross Weight (TOGW), Required Yield per Revenue Passenger Mile (\$/RPM) and Flyover Noise (FNOISE). The deviation function was taken to be an equal weighting of each of these three variables and is as follows in Eq. (2):

$$Z = 0.33 \text{ TOGW}^* + 0.33 \text{ FNOISE}^* + 0.33 \text{ \$/RPM}^* \quad (2)$$

Each of the deviation variables will be minimized and their goals will hopefully be simultaneously achieved. This formulation parallels the use of an overall evaluation criteria as a solution objective function.

An Archimedean Solution has been found using IMAGE. The results of this solution are in Table 2. Discretized wing parameters are normalized with respect to wing semi-span and system goals are normalized with respect to their targets. The \$/RPM goal was not achieved in this solution. DSIDES did however find a solution that minimizes the deviation function. During the solution process, it was found that the bounds on the Thrust-Weight Ratio are too small to affect the solution and should be increased in further studies. The baseline and final planform shapes are compared in Figure 13.

Table 2. Design Space Search Results

	Baseline	Archimedean Solution
System Variables		
Leading Edge Kink (X1)	1.62	1.54
Leading Edge Tip (X2)	2.23	2.10
Trailing Edge Tip (X3)	2.49	2.40
Trailing Edge Kink (X4)	2.28	2.20
Root Chord (X5)	2.35	2.19
Kink Y Positions (Y1)	0.51	0.55
Wing Position (XWING)	0.29	0.29
Thrust-Weight Ratio (TW)	0.31	0.32
Wing Area (SREF)	8500.0 ft ²	8583.1 ft ²
Goals		
Takeoff Weight (TOGW)	1.114	0.98
Required Yield / RPM (\$/RPM)	1.344	1.23
Flyover Noise (FNOISE)	0.970	0.95
# FLOPS Calls		171
Solution Time		25 Hours

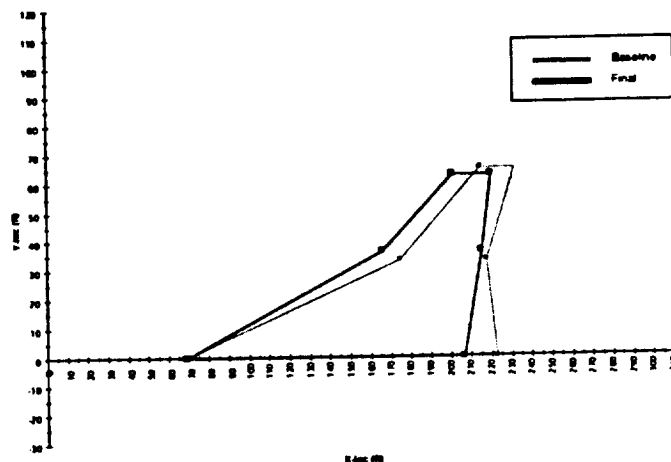


Figure 13. Planform Comparison: Baseline vs. DSP Solution

Each FLOPS execution took approximately 8 minutes on an RS6000/320H. Because of calculation time and that accuracy is not necessary required during early conceptual design, solution tolerance was set at 10%. IMAGE requires less than 30 seconds per FLOPS execution for data handling and solution calculations through DSIDES.

IMAGE was found to be an easy way to configure and link this design problem. FLOPS was made into an agent and integrated into the system in less than a day and the actual wing design problem was configured in the same amount of time. With IMAGE, alternative deviation functions can be entered (this will be discussed in the next section) and solved using IMAGE. Variable history during solution is stored within IMAGE so that results similar to those discussed here can easily be generated.

Finally, in addition to verifying the statistical accuracy of the RSE, it is of interest to examine how well the equation predicts the response for a point outside the DOE database. This was done by running the wing design procedure of Figure 8 using the Archimedean solution design variable results from Table 2. The percent error of the RSE prediction in relation to the ASTROS/ISMD appears acceptable, though it certainly warrants an examination of more data points for a more definite confirmation. The comparison is shown in Table 3.

Table 3. RSE Error at Solution Point

	ASTROS/ ISMD	RSE	RSE % Error
Wing Structural Weight	34,448 lbs.	37,776 lbs.	-9.66 %

3. A PARALLEL STUDY FOR WING DESIGN DATA STRUCTURES

During the course of implementing this design scenario in IMAGE, the need to have a well defined data model became evident. In addition, research has shown that advances in the aircraft technologies have resulted in an increase in the amount of data required to define a design during the conceptual stages [Hall (96a)]. A conceptual design dictates a close multidisciplinary effort requiring large amounts of data exchange. In order to optimize the design process, it is crucial that a top-down data management design structure be in place in the early phases of the design. This structure will provide consistency in data format and allow ease of data exchange between the various disciplines involved in the design process. In the conceptual design phase, consideration must be given to the changing structure of the database as the product design evolves. Current database design approaches are typically limited to the detailed design phase where the data organization is fixed.

The complexity of an HSCT design problem dictates a close multidisciplinary effort requiring large amounts of data exchange. This problem is illustrated in Figure 14. Moreover, with the enormous development costs associated with such a design, corporate teaming is essential. It is critical to the success of the HSCT and future aircraft design that a new approach be taken toward the management and exchange of information. A top-down data management design structure should be developed and implemented in the early stages in order to optimize the design process.

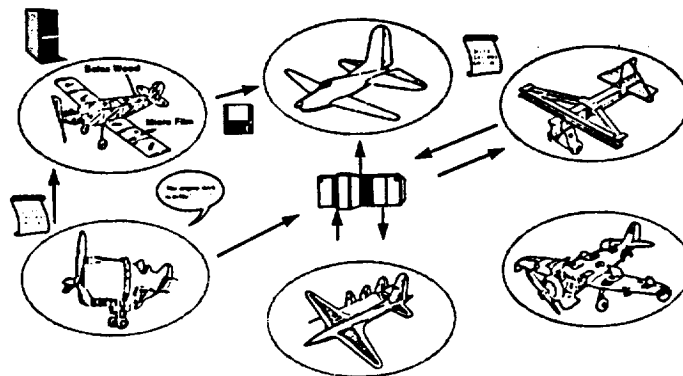


Figure 14. The data management problem

The data modeling problem is experienced for both design process and product models. Hall has investigated the use of IDEF0 structures for representing a design. These are shown in Figure 15 and Figure 16. The use of these diagrams can be extended to the use of design Palettes as was done for the AFW problem. A graphical interface was given in Figure 12.

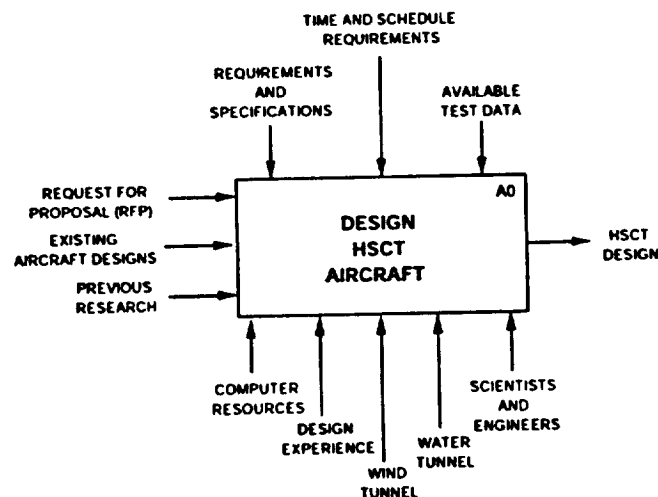


Figure 15. IDEF0 - Level 0

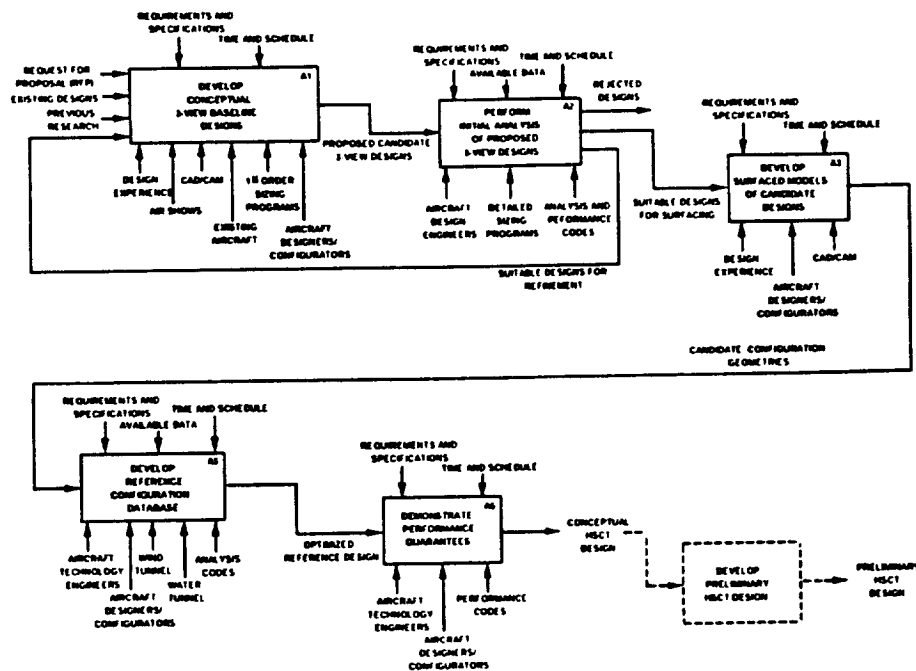


Figure 16. IDEF0 Diagram - Level 1.

A data model is also required for the product information. Figure 17 shows the IDEF1X model for typical aircraft components. In this example, an aircraft configuration is made up of the components engine, fuselage, gear, inlet, nozzle, canard, horizontal, vertical, and wing. This type of data model is also utilized within the IMAGE architecture.

		Year 1 Problem Definition	Year 2 Problem Development	Year 3 Problem Solution
Students	Dan DeLaurentis			
	Jae-Moon Lee			
	Jason Har			
	Neil Hall			
	Patrick Koch			
	Scott Zink			
	Timothy Simpson			
	Srinivas Vadde			
	Dr. Carlos Cesnik			
	Dr. Wei Chen			
	Dr. Mark Hale			
	Dr. Kemper Lewis			
	Dr. William Marx			
Faculty	Dr. Peter Röhl			
	Dr. Sang Synn			
	Dr. Daniel Schrage			
	Dr. James Craig			
	Dr. Farrokh Mistree			
Industry	Dr. Robert Fulton			
	Dr. Dimitri Mavris			
	Rockwell International			
	Lockheed Martin			
	Boeing			
	General Electric			
	Wright Laboratory			
	NASA Langley			

Figure 18. Three Year Involvement

NEW APPROACHES TO HSCT MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

Year 3 Presentations, Publications and Workshops
Grant NGT 51102L

December 31, 1996

The following workshops and publications (referencing support from the Grant 51102L) were accomplished under the third year's research effort:

- Bras, B. A. and F. Mistree, "Designing Design Processes in Decision-Based Concurrent Engineering," SAE Transactions Journal of Materials & Manufacturing, vol. 100, no. , pp. 451-458, Warrendale, PA, SAE International, 1991.
- Chen, W., A Robust Concept Exploration Method for Configuring Complex Systems, Ph.D. Dissertation, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, 1995.
- DeLaurentis (96a), D. A., Mavris, D.N., "An IPPD Approach to the Preliminary Design Optimization of an HSCT using Design of Experiments", 20th ICAS Congress, Sorrento, Italy, September 1996.
- DeLaurentis (96b), D. A., C. E. S. Cesnik, J.-M. Lee, D. N. Mavris and D. P. Schrage, "A New Approach to Integrated Wing Design in Conceptual Synthesis and Optimization," Sixth AIAA / NASA / USAF / ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996. AIAA-96-4174.
- Hale (96a), M. A., J. I. Craig, F. Mistree and D. P. Schrage, "DREAMS & IMAGE: A Model and Computer Implementation for Concurrent, Life-Cycle Design of Complex Systems," Concurrent Engineering: Research and Applications, vol. 4, no. 2, pp. 171-186, June 1996.
- Hale (96b), M. A. and J. I. Craig, "Techniques for Integrating Computer Programs into Design Architectures," Sixth AIAA / NASA / USAF / ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996. AIAA-96-4166.
- Hale (96c), M. A., "An Open Computing Infrastructure that Facilitates Integrated Product and Process Development from a Decision-Based Perspective," Doctoral Dissertation, Georgia Institute of Technology, School of Aerospace Engineering, July, 1996.
- Hall (96a), Neil S. and Fulton, Robert E., "An Investigation of a Relational Database Approach to a Multidisciplinary Conceptual Design for the HSCT", 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, California, August 18-22, 1996, Paper Number 96-DETC/EIM-1425.
- Hall (96b), Neil S. and Fulton, Robert E., "Impact of Data Modeling and Database Implementation Methods on the Optimization of Conceptual Aircraft Design", Research Paper, School of Mechanical Engineering, Georgia Institute of Technology, 1996.
- Integrated Structures/Maneuver Design Program*, Rockwell International, North American Aircraft, 1995.
- Mavris, D.N., Bandte, O., and Schrage, D.P., "Economic Uncertainty Assessment of an HSCT Using a Combined Design of Experiments/Monte Carlo Simulation Approach", 17th Annual Conference of the International Society of Parametric Analysts, San Diego, CA, May 1995.
- Miller, G.D., "An Active Flexible Wing Multidisciplinary Design Optimization Method", AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, 7-9 September 1994.
- Mistree, F., Hughes, O.F., and B.A. Bras, *The Compromise Decision Support Problem and the Adaptive Linear Programming Algorithm*, E. Kamat, M.P., Structural Optimization: Status and Promise, Washington DC, (pp. 247-286), AIAA, 1993.
- Röhl, P.J., "A Multilevel Decomposition Procedure for the Preliminary Wing Design of a High Speed Civil Transport Aircraft," Ph.D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, June 1995.
- Synn, Sang Y. and Fulton, Robert E., "Prediction of Parallel Computing Performance", Research Paper, Parallel Processing Lab, School of Mechanical Engineering, Georgia Institute of Technology, 1996.

Workshops Supported by NASA Grant NGT 51102L:

HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1996.

October 16, 1995

The following workshops and publications (referencing support from the Grant 51102L) were accomplished under the second year's research effort:

- Chen, W., Allen, J.K., Mavris, D.N., Mistree, F., Tsui, K.-L., 1995b, "Integration of Response Surface Method with the Compromise Decision Support Problem in Developing a General Robust Design Procedure," *Advances in Design Automation* (Azarm, S., et al. Eds.), New York: ASME, 1995, pp. 485-492. ASME DE-Vol. 82-2.
- Chen, W., Allen, J.K., Mavris, D.N., Mistree, F., 1995c, "Robust Concept Exploration for Developing the Top-Level Specifications of Complex Systems," *Engineering Optimization*, (in press).
- Chen, W., 1995a, A Robust Concept Exploration Method for Configuring Complex Systems, Ph.D. Dissertation, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
- Hale, M. A., 1994a, "Preliminary Agent Technologies with CATIA," presented at the CATIA Operators Exchange Meeting, Dallas, October 9-13.
- Hale, M. A., 1994b, "IMAGE: A Design Integration Framework Applied to the High Speed Civil Transport," HM301: First University/Industry Symposium on High Speed Civil Transport Vehicles, North Carolina A&T State University, December 4-6.
- Hale, M.A., 1995a, "A Computing Infrastructure that Facilitates Integrated Product and Process Development from a Decision-Based Perspective," Ph.D. Thesis Proposal, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, January.
- Hale, M. A. and Craig, J. I., 1995b, "Use of Agents to Implement and Integrated Computing Environment," *Computing in Aerospace 10*, AIAA, San Antonio, TX, March 28-30, Preprint: AIAA-95-1001.
- Hale, M. A., Craig, J. I., Mistree, F., Schrage, D. P., 1995c, "Implementing an IPPD Environment from a Decision-Based Design Perspective," ICASE/LaRC Workshop on Multidisciplinary Design Optimization, Hampton, VA, March 13-16.
- Hale, M. A., Craig, J. I., Mistree, F. and Schrage, D.P., 1995d, "On the Development of a Computing Infrastructure that Facilitates IPPD from a Decision-Based Design Perspective," 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Anaheim, CA. Preprint AIAA-95-3880.
- Hall, N., and Fulton, R.E., "A Relational Database Application to Multidisciplinary Conceptual Design for HSCT," (Submitted for the publication).
- Lewis, K., Lucas, T. and Mistree, F., 1994, "A Decision-Based Approach for Developing A Ranged Top-Level Aircraft Specification: A Conceptual Exposition," AIAA/NASA/USAF/ ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, Florida, 465-481. Paper No. AIAA-94-4304-CP.
- Lewis, K. and Mistree, F., 1995a, "On Developing a Taxonomy for Multidisciplinary Design Optimization: A Decision-Based Perspective," First World Congress of Structural and Multidisciplinary Optimization, Goslar, Germany. Paper number 118.
- Lewis, K. and Mistree, F., 1995b, "Designing Top-Level Specifications: A Decision-Based Approach to a Multiobjective, Highly Constrained Problem," 36th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, New Orleans, LA. pp. 2393-2405.
- Lucas, T., 1995a, Formulation and Solution of Hierarchical Decision Support Problems, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
- Lucas, T., Vadde, S., Chen, W., Allen, J.K. and Mistree, F., "Utilization of Fuzzy Compromise DSPs for Hierarchical Design Problems", 1994, AIAA/ASME/ASCE/AHS/ACS 35th Structures, Structural Dynamics and Materials Conference, Hilton Head, South Carolina, pp. 1753-1763. Paper No. AIAA-94-1543-CP.
- Mistree, F., Lewis, K. and Stonis, L., 1994, "Selection in the Conceptual design of Aircraft," AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, Florida, 1153-1166. Paper No. AIAA-94-4382-CP.
- Röhl, P.J., Mavris, D.N., and Schrage, D.P., 1994, "A Multilevel Decomposition Procedure for the Preliminary Wing Design of High-Speed Civil Transport Aircraft," First Industry/Academy Symposium on Research for Future Supersonic and Hypersonic Vehicles, Greensboro, NC, December.
- Röhl, P.J., Schrage, D.P. and Mavris, D.N., 1995a, "Combined Aerodynamic and Structural Optimization of a High-Speed Civil Transport Wing," 36th AIAA Structures, Dynamics, and Materials Conference, New Orleans, LA, April, Preprint AIAA 95-1222.
- Röhl, P.J., 1995b "A Multilevel Decomposition Procedure for the Preliminary Wing Design of a High Speed Civil Transport Aircraft," Ph.D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, June 1995.

- Röhl, P.J., Mavris, D.N., and Schrage, D.P., 1995b, "Preliminary HSCT Wing Design Through Multilevel Decomposition," 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Los Angeles, CA, September 19-21, AIAA 95-3944.
- Simpson, T.W., 1995a, Development of a Design Process for Realizing Open engineering Systems, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, August 1995.
- Simpson, T.W., Bauer, M.D., Allen, J.K. and Mistree, F., 1995b, "Implementation of DFA in Conceptual and Embodiment Design using Decision Support Problems," *ASME Advances in Design Automation* (Azarm, S., et al. Eds.), New York: ASME, pp. 485-492. ASME DE-Vol. 82-2.
- Synn, S.Y. and Fulton, R.E., 1994a, "The Concurrent Element Level Processing for Nonlinear Dynamic Analysis on a Massively Parallel Computer", Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, (also in *Journal of Computer Systems in Engineering*).
- Synn, S.Y. and Fulton, R.E., 1994b, "The Prediction of Parallel Skyline Solver and its Implementation for Large Scale Structural Analysis," Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, (Also, in *Journal of Computer Systems in Engineering*).
- Synn, S.Y., 1995a, "Practical Domain Decomposition Approaches for Parallel Finite Element Analysis," Ph.D. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, January 1995.
- Synn, S.Y. and Fulton, R.E., 1995b, "Practical Strategy for Soncurrent Substructure Analysis," *Journal of Computers & Structures*, Vol.54, No.5.
- Synn, S.Y., Schwan, K., and Fulton, R.E., 1995c, "Analysis of Large Scale Heterogeneous Structures on Massively Parallel Computers," *Journal of Concurrency: Practice and Exercise* (Submitted for the publication in the *Journal of Concurrency, Practice/Experience*).
- Vadde, S., 1995, *Modeling Multiple Objectives and Multilevel Decisions in Concurrent Design of Engineering Systems*, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
- Vadde, S., Allen, J.K., Lucas, T. and Mistree, F., 1994, "On Modeling Design Evolution along a Design Time-Line," *AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Panama City, Florida, 1474-1482. Paper No. AIAA-94-4313-CP.

Workshops Supported by NASA Grant NGT 51102L:

HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1995.

October, 1994

The following workshops and publications (referencing support from the Grant 51102L) were accomplished under the second year's research effort:

- Hale, M. and J. Craig, "Preliminary Development of Agent Technologies for a Design Integration Framework," AIAA-94-4297, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Hall, N., and R. Fulton, "A Relational Database Approach to a Multidisciplinary Conceptual Design for the HSCT," Georgia Institute of Technology, September, 1994.
- Lewis, K., T. Lucas and F. Mistree, "A Decision-Based Approach for Developing Ranged Top-Level Aircraft Specifications: A Conceptual Exposition," AIAA-94-4304, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Lucas, T., S. Vadde, W. Chen, J. Allen, and F. Mistree, "Utilization of Fuzzy Compromise DSPs for Hierarchical Design Problems," AIAA-94-1543, AIAA/ASME/ASCE/AHS/ACS 35th Structures, Structural Dynamics and Materials Conference, Hilton Head, SC, April, 1994.
- Marx, W., D. Schrage and D. Mavris, "Integrated Product Development for the Wing Structural Design of the High Speed Civil Transport," AIAA-94-4253, 5th AIAA/ NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Marx, W., D. Schrage and D. Mavris, "Integrated Design and Manufacturing for the High Speed Civil Transport," ICAS-94-10.8.3, 19th ICAS Congress/AIAA Aircraft Systems Conference, Anaheim, CA, September, 1994.
- Mistree, F., K. Lewis and L. Stonis, "Selection in the Conceptual Design of Aircraft," AIAA-94-4382, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Röhl, P., D. Schrage and D. Mavris, "A Multilevel Wing Design Procedure Centered on the ASTROS Structural Optimization System," AIAA-94-4411, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.
- Vadde, S., J. Allen, and F. Mistree, "On Modeling Design Evolution Along a Design Time-Line," AIAA-94-4313, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

Workshops Supported by NASA Grant NGT 51102L:

- HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, December 1993.
- HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1994.

APPENDIX E. ACCOMPANYING CDROM

A CDROM accompanies this Final Report and contains electronic versions of most of the publications, theses, and design project reports developed under Grant funding. The files are all in Adobe PDF format with the exception of 3 Microsoft PowerPoint 97 files that were too complex to convert to PDF format and so are included in their native format.

The simplest way to access this CD is to use a web browser such as Internet Explorer 4 or Netscape Navigator 4 (or newer). Or it is possible to go directory to the appropriate folder and copy the particular file that is needed. Adobe Acrobat Reader will be required to view the PDF files and PowerPoint 97 will be required to display 3 of the Report files.

To access this information using a web browser, insert the CDROM in the appropriate drive and open it on the desktop. The root directory will list the following:

- index.htm (STARTING POINT: double-click on this file to open a browser window that contains an index to the rest of the CDROM)
- Folder: Publications (contains copies of all of the papers presented or published)
- Folder: Reports (contains copies of the design project reports for 1996-1999 along with a PDF copy of this Final Report).
- Folder: icons (contains utility icons used with index.htm)

From the web browser window, it is possible to access all of the contents of the CDROM and to either view them, print them or copy them to local disks. Please note that some of the material is listed but electronic copies are not included because they were unavailable at the time of this printing.